Incentive Mechanisms for the Enforcement of Collaboration between Internet Service Providers

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HERACLITUS II Scholarship

European Union
European Social Fund

OPERATIONAL PROGRAMME
EDUCATION AND LIFELONG LEARNING
investing in knowledge society
MINISTRY OF EDUCATION & RELIGIOUS AFFAIRS, CULTURE & SPORTS
MANAGING AUTHORITY

Co-financed by Greece and the European Union

NSRF 2007-2013
programme for development
EUROPEAN SOCIAL FUND

I would like to dedicate this thesis to my loving parents ...

Acknowledgements

And I would like to acknowledge ...

Abstract

The emergence of new network applications, new technologies and richer network capabilities led to the wide spread of the Internet. Many of these new applications involve audio and/or video transfers. Peer-to-peer (P2P) file sharing, with BitTorrent as the dominant protocol, and Real-Time Entertainment (streaming video and audio) share the greatest percentage of the total Internet traffic today [1]. Also, Cloud Computing gains constantly increasing acceptance, with video and audio streaming being strong factors of the growth of cloud traffic. Thus, the growth of Internet implies the exchange of huge amounts of data among the various types of providers of the Internet ecosystem, namely Network Service Providers (NSPs), Over-The-Top Providers (OTTs), Application Providers, etc., which are inter-connected to each other in order to deliver applications to both household and business customers. This exchanging of traffic among providers may reduce the quality of the provided services due to the crossing inter-domain links with bottlenecks and more importantly impose high costs to the NSPs due to the charges of the inter-domain traffic. The topic of the present doctoral research work is to design and evaluate incentive mechanisms that aim at the promotion of collaboration among the inter-connected providers, in order to achieve reduced costs for inter-domain traffic, efficient resource management and increased profits through the improvement of Quality of Service (QoS) that the users experience and the creation of new applications.

The first part focuses on P2P file sharing, and especially on BitTorrent, which is both an important application (in terms of generating traffic) and an appropriate one for applying optimization mecha-

nisms. The collaboration mechanisms designed and evaluated incentivize Network Service Providers (NSPs), Application Providers and end-users to select data sources in such a way that the charges of the NSPs are reduced and the quality of the service provided to the users is enhanced (or at least maintained) at the same time. The mechanisms introduced exploit not only locality (selection of peers belonging to same network) and proximity (selection of peers according to the number of BGP hops away), as done in the literature, but also the business relationships between NSPs of either the same or different Tiers. The collaboration among the NSPs is defined as the explicit exchange of specific parameters about their preferences concerning remote sources (NSPs) or parts of the content (which subsequently affect the rankings), and the agreement of the NSPs about these parameters. All innovative approaches specified are evaluated extensively by means of a variety of simulations, and their performance is compared to mechanisms proposed in the literature, regarding their impact to the charged inter-domain traffic and the performance of the peers. The assessment reveals that large NSPs benefit considerably by collaborating with each other, creating large clusters within which they promote locality and thus attain lower charges for inter-domain traffic, without affecting the performance of their users. Moreover, these NSPs can further benefit if they provide their customers NSPs with the incentive to collaborate with them, e.g. by giving to them part of their extra benefits attained. Application Providers and end-users can be motivated to use these mechanisms by the improvement in the performance of the service or, if this is not the case, by specific incentives that should be given to them by the NSPs that gain from this collaboration.

The second part focuses on network services of predefined end-to-end QoS provided at the inter-domain level. Important such services to which the relevant results apply are the delivery of CDN content with assured high quality and services based on the provision of cloud resources. To this end, inter-carrier coordination schemes for the formation of bundled SLAs creating end-to-end paths of assured quality of service are studied. Such schemes specify the necessary information that has to be made available to the participating providers, the way of distributing this information, the way of exchanging and bundling SLAs and the entity that coordinates this bundling (if any). The revelation of information by one NSP to another greatly affects the total price of the service, the imbalance in revenue sharing among the providers and even the provision of the service. Six practically applicable coordination schemes are investigated for the provision of services requiring on end-to-end inter-domain QoS. The study focuses on the information issues resulting by the use of each coordination scheme, the consequences of which are studied further by deriving the corresponding equilibrium pricing strategies by means of game-theoretic analysis. The numerical evaluation of the profits and the assessment of the loss of efficiency (regarding the probability for the service to be indeed offered) compared to a benchmark collaborative model show that the selfish behaviour of the providers combined with incomplete information, may possibly lead to a highly unfair revenue distribution in favour of the first provider in the chain and loss of efficiency due to cases of failure of service provision. Finally, guidelines for the choice of the appropriate coordination scheme in practical cases are provided, depending on the maturity of the market and on properties of the demand for cloud and connectivity services.

Περίληψη

Το Internet αποτελεί πιά αναπόσπαστο εργαλείο για εκατομμύρια χρήστες στον κόσμο είτε εταιρικούς είτε απλούς καταναλωτές. Η εξάπλωσή του αλλά και η συνεχής του ανάπτυξη οφείλονται τόσο στις τεχνολογικές εξελίξεις όσο και στη δημιουργία καινούριων εφαρμογών. Πολλές από αυτές τις εφαρμογές αφορούν τη μεταφορά αρχείων ήχου και εικόνας ή video. Το μεγαλύτερο ποσοστό της κίνησης Internet οφείλεται σε εφαρμογές ομότιμου διαμοιρασμού αρχείων (Peer-to-peer (P2P) file sharing) αλλά και εφαρμογές πραγματικού χρόνου (Real-Time Entertainment). Επίσης η χρήση του Νέφους (Cloud Computing) συνεχώς αυξάνεται ενώ οι εφαρμογές που αφορούν video παίζουν σημαντικό ρόλο στην αναπτυξή του. Η μεγάλη αυτή αύξηση στην συνολική κίνηση, επηρεάζει και την κίνηση μεταξύ των διαφόρων παρόχων υπηρεσιών, όπως Παρόχων Internet (Network Service Providers), Παρόχων Περιεχομένου Over-The-Top Providers, Παρόχων Εφαρμογών Application Providers κτλ. που συνδέονται μεταξύ τους. Η κίνηση αυτή μπορεί να επηρεάσει την ποιότητα των υπηρεσιών που απολαμβάνουν οι χρήστες και συνήθως επιφέρει μεγάλα κόστη για τους παρόχους εξαιτίας των χρεώσεων που επιβάλλονται σε αυτή. Στόχος της παρούσας ερευνητικής εργασίας είναι η σχεδίαση και η αξιολόγηση μηχανισμών κινήτρων για την προώθηση της συνεργασίας μεταξύ των παρόχων ώστε να επιτύχουν μείωση του κόστους που προέρχεται από την μεταξύ τους κίνηση, καθώς και αποδοτική διαχείριση των πόρων και αύξηση των κερδών τους μέσα από την βελτίωση της ποιότητας υπηρεσίας των χρηστών και της δημιουργίας νέων εφαρμογών.

Ένα μέρος της παρούσας ερευνητικής εργασίας στοχεύει στην κίνηση που δημιουργείται από τις P2P εφαρμογές και ειδικά το πρωτόκολλο

BitTorrent. Οι μηχανισμοί συνεργασίας που σχεδιάστηκαν και αξιολογήθηκαν στα πλαίσια της εργασίας παρέχουν τα κατάλληλα κίνητρα στους Παρόχους Internet, Περιεχόμένου, Εφαρμογών αλλά και στους χρήστες, ώστε να επιλέξουν τις κατάλληλες εναλλακτικές πηγές δεδομένων κυρίως μέσα από το δίκτυο στο οποίο ανήκουν και οι ίδιοι για να επιτύχουν μείωση των χρεώσεων στους Πάροχους Internet και αν είναι δυνατόν βελτίωση της ποιότητας που απολαμβάνουν οι χρήστες. Οι μηχανισμοί μας χρησιμοποιούν τις επιχειρηματικές σχέσεις που ήδη έχουν μεταξύ τους οι Πάροχοι Internet , είτε αυτοί ανήκουν στο ίδιο επίπεδο (Tier) ή σε διαφορετικό. Με βάση τις σχέσεις αυτές οι Πάροχοι κατατάσσουν τους διάφορους χρήστες σε τοπικούς ή απομακρυσμένους (και πόσο). Η κατάταξη αυτή επιτρέπει στους τοπικούς χρήστες να καθορίσουν μία σειρά προτεραιότητας χρηστών από τους οποίους 'κατεβάζουν' περιεχόμενο. Επίσης σε περίπτωση προϋπάρχουσας συνεργασίας, οι Πάροχοι μπορούν διαχωρίσουν το περιεχόμενό σε δύο μέρη. Κατεβάζοντας ο κάθε ένας δοαφπρετικά μέρη από συνδέσεις που φέρουν χρεώσεις και ανταλάσσοντας τα υπόλοιπα μέσω της δικής τους σύνδεσεις (που δε χρεώνεται) μπορούν να μειώσουν περεταίρω τα κόστη τους. Όλοι οι μηχανισμοί αξιολογήθηκαν μέσω προσομοιώσεων του δικτύου και η επίδοσή τους συγκρίθηκε με αυτή άλλων μηχανισμών από τη βιβλιογραφία τόσο ως προς την επίδοση των χρηστών όσο και ως προς τις χρεώσεις των Παρόχων. Τα πειράματα έδειξαν κυρίως ότι οι μεγάλοι Πάροχοι που έχουν αρκετές συνδέσεις με άλλους παρόχους ή και αρκετούς χρήστες που συμμετέχουν στην ανταλλαγή των δεδομένων, έχουν μεγαλύτερα κίνητρα για να συνεργαστούν με άλλους παρόχους δημιουργώντας ομάδες Πάροχων μέσα στις οποίες προωθείται η τοπικότητα της κίνησης.

Οι Πάροχοι ακολουθούν ένα κατανεμημένο σύστημα συνεργασίας αναπτύσσοντας μεταξύ τους μεγάλης διάρκειας συμβόλαια. Τα από-άκρη-σε-άκρη μονοπάτια δημιουργούνται από την ένωση των διαφόρων παρόχων μέσω των συμβολαίων τους. Παρόλο, όμως, που αυτό το είδος των συμβολαίων επιτρέπει την σύνδεση ενός χρήστη με όλο το Internet , αυτό δε βοηθάει ιδιαίτερα άλλες εφαρμογές οι οποίες απαιτούν τη συνεργασία περισσότερων από δύο παρόχων στη σειρά. Τέτοιου είδους εφαρμογές, χρειάζονται κυρίως ένα συγκεκριμένο επίπεδο ποιότητας υπηρεσίας, και μπορεί να είναι για παράδειγμα η παροχή περιεχομένου με ποιότητα υπηρεσίας. Έτσι στην παρούσα ερευνητική εργασία, παρέχουμε μοντέλα που επιτρέπουν την συνεργασία τριών ή και περισσότερων παρόχων για τη προσφορά μίας υπηρεσίας. Πάνω σε αυτά τα μοντέλα εξετάζουμε τα διαφορετικά προβλήματα που προκύπτουν εξαιτίας της ασύμμετρης πληροφόρησης των συμμετεχόντων και πως αυτά επηρεάζουν τη συνολική τιμή της υπηρεσίας, το διαμοιρασμό των κερδών στους παρόχους και την επιλογή των παρόχων που θα προσφέρουν την υπηρεσία. Επίσης αναλύουμε ορισμένα προβλήματα που προκύπτουν από την ασύμμετρη πληροφόρηση μέσω μαθηματικής μοντελοποίησης. Τα αποτελέσματα δείχνουν ότι η 'έγωιστική' συμπεριφορά των παρόχων μπορεί να προκαλέσει μεγάλη ανομοιογένεια στο διαμοιρασμό των κερδών καθώς και αποτυχία προσφοράς της υπηρεσίας.

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Chapter 1

Introduction

Internet traffic has exploded in the recent years, due to the wide spreading of a multitude of applications, producing video traffic, as mush as the 57% of all Internet traffic during 2012[2]. Network Service Providers (NSPs), who offer connectivity to business customers and residential consumers (end-users), Content Delivery Networks (CDNs), who offer content, Application Providers and Cloud Providers, who offer services, along with the end-users have their own role in the increase of traffic. Also, usually the two ends, source and destination, which may be end-users or content, application or service providers, lay on different networks and the traffic crosses multiple NSPs until it reaches the destination. NSPs, have to deliver more and more traffic per time, which possibly is destined to any place in the world. This rises to mainly two problems to the NSPs; a. the large amounts of traffic crossing the borders of their networks causing possibly high costs and b. the dependence of the performance experienced on treatment of their traffic by other networks [3]. In this doctoral thesis we focus on **finding the appropriate incentive mechanisms to promote the collaboration among the NSPs for reducing their inter-domain traffic, while the performance experienced improves and thus providers and end-users adopt also the mechanisms, or assuring the provision of a certain level of QoS on end-to-end paths formed by three or more inter-connected providers**.

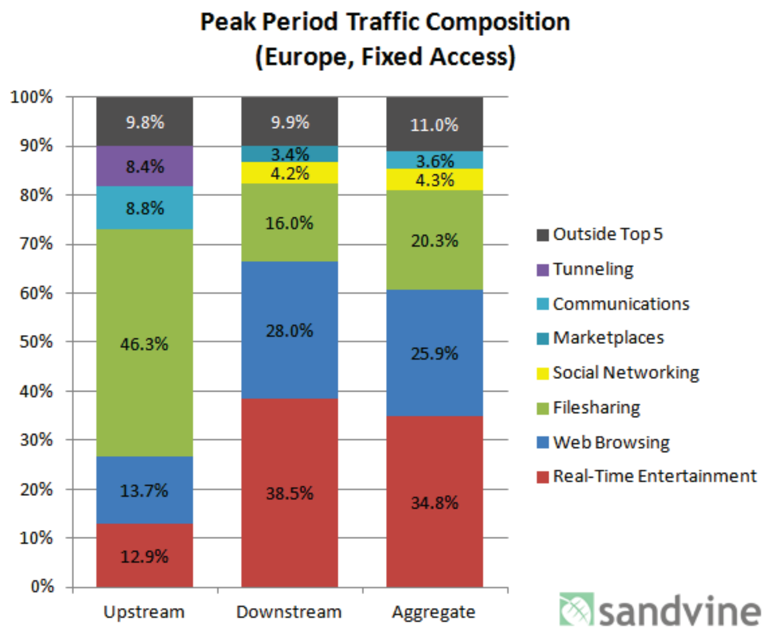

Figure 1.1: Peak Period Traffic Composition

1.1 Motivation

In this section we discuss the widespread of video and audio applications, to the traffic of which our mechanisms applies. As shown in Figure 1.1[1] the largest portion of fixed traffic in Europe in 2012, was produced by Real-Time applications, such as Netflix, YouTube etc., consisting mostly of streaming video and audio. Depending on the countries, the percentage of downstream peak traffic may range from 33.5% to over 50%.

Filesharing applications also produce high amount of traffic. They use Peer-to-Peer (P2P) protocols as BitTorrent, eDonkey, Gnutella, Ares, etc. From all of these protocols used, the largest amount of traffic is produced by BitTorrent, which has risen in volume by over 40% during 2012 [1]. In fact, Filesharing was more popular a few years ago, when this research work began. According to Ipoque studies [4], P2P generated 43 to 70% of all Internet traffic depending on the geographical area, in 2008. BitTorrent had the biggest share of that traffic, estimated around 80 %. Nowadays, "only" produces 10.31% worldwide of total

[1]Source: [1]

	Upstream		Downstream		Aggregate	
Rank	Application	Share	Application	Share	Application	Share
1	BitTorrent	31.8%	HTTP	26.3%	HTTP	24.1%
2	HTTP	11.4%	YouTube	22.3%	YouTube	20.1%
3	eDonkey	11.2%	BitTorrent	12.1%	BitTorrent	14.9%
4	YouTube	6.66%	Flash Video	3.95%	eDonkey	3.98%
5	Skype	6.00%	Facebook	3.71%	Facebook	3.76%
6	Facebook	4.07%	RTMP	2.90%	Flash Video	3.54%
7	Teredo	3.44%	eDonkey	2.78%	RTMP	2.63%
8	SSL	3.09%	MPEG	2.53%	MPEG	2.26%
9	Flash Video	1.09%	iTunes	2.25%	Skype	2.13%
10	RTMP	1.01%	Skype	1.48%	iTunes	2.04%
	Top 10	**79.76%**	**Top 10**	**80.30%**	**Top 10**	**79.44%**

Figure 1.2: Top 10 peak period applications (Europe, Fixed Access)

peak traffic [1], which however, is not enough to remove it from the first position in upstream and third in aggregated traffic of the top 10 applications used in Europe at peak period time during 2012, as shown in Figure 1.2[1].

Throughout the duration of this research, we constantly examined the trends and the expectations/predictions for the applications in future. Sandvine, in its research report in 2012, [1], predicted that Real-Time Entertainment will account for over two-thirds of peak period traffic by 2015. Interesting studies have been also conducted by Cisco [5]. and concentrate on Cloud Computing. They predict that annual global cloud IP traffic will reach 4.3 zettabytes by the end of 2016, thus indicating a six-fold increase from 2011-2012. Also, Clouds are expected to be used widely for Real-Time and video applications. The main drivers for Cloud adoption include faster delivery of services and data, increased application performance, as well as improved operational efficiencies. Clouds support increased virtualization, standardization, and automation, which in their turn lead to increased performance, as well as higher capacity and throughput, crucial as already mentioned for the networks of the future. Conclusively, two main categories of applications generate huge amount of traffic and are expected to keep doing so in the near future; P2P applications and Real-Time Entertainment ones among with Cloud Computing. P2P applications usually provide an acceptable performance to the end-users, but they may create overlay paths, which may impose costs to the NSPs, when charged inter-domain links are used. Real-Times Entertainment

[1] Source: [1]

applications may face performance degradation when their traffic passes through different networks, since they are more sensitive to delay, jitter and bandwidth parameters. The research of this Ph.D. Thesis addresses both of these problems.

Motivation
Video and audio applications produce huge amounts of traffic, which usually travels through multiple networks and inter-domain links. In case of P2P applications, huge costs may be imposed to the providers. Real-Time applications on the other hand may face performance degradation since their traffic highly depends on parameters such as delay or jitter, which can variable across the multiple networks.

1.2 Objectives

P2P applications take no consideration of the physical networks. NSPs are aware of their networks' status, i.e., the capacity of their links, their costs, peak times, traffic patterns, number of users and of course the physical topology. However, this information is kept hidden from the end-users and their P2P applications. On the other hand, end-users do not provide any information about their connection preferences and the applications create overlay networks based only on their own information about other peers in the network. This information asymmetry incommode the management of the traffic by the NSPs, which has a significant impact on network efficiency, application performance or user experience and economics. Inter-domain traffic, or in other words traffic that crosses the borders of a network, may impose high costs to the NSPs. The links between NSPs belong to two main categories, i.e., transit and peering links (see Chapter 2). Traffic that passes through transit links is charged, while the traffic that passes through peering links is not. However, peering links are based on the assumption that traffic is symmetric; Thus, a predetermined ratio of traffic expressing the highest acceptable level of asymmetry is agreed. Regularly, if this ratio is violated, a fee is imposed. Also, wrong estimation of traffic patterns may lead to inefficient routing, which lead to low service performance. Due to the information asymmetry and the inefficient traffic management, **inter-domain traffic may**

lead to imposition of high costs to the NSPs and also may degrade the performance of the applications and thus the QoS that the users experience. In the first part of this Ph.D. Thesis, we propose and analyse mechanisms that provide the appropriate incentives to the NSPs to collaborate with each other in order to reduce the costly inter-domain traffic without affecting the ratio of traffic of the peering links, while at the same time improve, or at least not affect, the download times of the end-users, giving them the incentive to adopt the mechanisms.

On the other hand, Real-Time applications, may need QoS assurance especially when they cross the links that connect two different domains. The network, where the traffic is terminating may face congestion, degrading the performance of the application. Of course, not only Real-Time applications, but also each applications that may need their traffic to cross two or more networks with QoS assurance falls into this category. Also, Cloud Computing becomes increasingly popular nowadays. NSPs and Cloud Providers, which may be Infrastructure as a Service (IaaS), Platform as a Service (PaaS) or Software as a Service (SaaS) providers, need to employ resource reservation control mechanisms to guarantee a customized level of performance and availability of the offered services throughout the whole end-to-end path (from end-user access provider to the application or IaaS provider) [6]. **QoS provides the level of assurance that guarantees the resource requirements of a service, according to the end-user's needs, while the associated Service Level Agreements (SLAs) provide the means of agreement between the involved participants upon the required level of QoS** [7]. These SLAs differ from the static and long term bilateral transit and peering SLA interconnection agreements between providers. Since the QoS-enabled services are provided on top of the basic interconnection services for traffic exchange, the SLAs can have shorter time scales and charged at extra prices. **For the provision of end-to-end QoS assurance the participants in the value chain have to coordinate with each other for exchanging the necessary information in order to form the end-to-end SLAs or else bundled SLAs.** The bundled SLAs are created by concatenating the sub-SLAs of each provider that participate in the end-to-end path. Note here that the participants may be NSPs, CDNs, Cloud Providers and generally any provider that is willing to offer a service with a certain QoS level to a customer that relies on a different network. The way of coordination is described by the so called coordination schemes. A complete such coordination scheme should encompass all the financial and information-sharing interactions among providers that enable their interconnection for the provision of the bundled SLA required, while at the same time, it must be easily deployable on the top of the current Internet and cloud architecture.

Objectives
We propose and analyse mechanisms that aim to provide the appropriate incentives to the providers in order for them to collaborate for:

1. *Reduction of costly inter-domain traffic:*. We propose the appropriate incentives mechanisms to the NSPs in order to collaborate for reducing the costly inter-domain traffic without affecting the ratio of traffic in peering links and maintaining or improving the performance of the application. Indirect incentives should be given to the Application providers and the end-users in order to adopt the mechanisms. In other words, the mechanisms aim to reach a **Win-Win** or at least a **Win-No Lose** situation for NSPs and their end-users.

2. *Enabling the provision of end-to-end services with a specified QoS level:*. Our coordination schemes aim to provide the means for collaboration between multiple providers that create an end-to-end path from a source to a destination, for the formation of bundled SLAs that enable the provision of a service with a specified QoS level.

1.3 Main Contribution and Conclusions

In the first part of this Ph.D. Thesis we propose incentive mechanisms that aim at the reduction of the inter-domain traffic of the NSPs, where charges apply. Extensive research work has been carried out, see section 2.2, aiming at the reduction of the inter-domain traffic and, consequently, of the associated costs of the NSPs. This work led to overlay traffic management techniques, referred to as locality-awareness mechanisms, which are successful from the NSPs' point of view, since they increase the level of locality of the traffic. This is achieved by distinguishing the local peers (belong to the same network) from the non-local ones, and the non-locals according to proximity (BGP hops away). However, none of these approaches **distinguish the non-local peers according to the business relationships that the NSPs form with each other**. In our research we do introduce a distinction which is very important, only because it may lead to a significant "targeted" reduction of the transit inter-domain traffic, in the links where charging applies, thus serving better the objective of reduction of the relevant charges.

In particular, we propose and analyse appropriate mechanisms that incentivize NSPs to select alternative data sources mainly from the already collaborative networks in such a way that the charges of the NSPs are reduced and the quality of the service that is provided to the end-users is enhanced at the same time. Three incentive mechanisms that promote further collaboration among NSPs have been introduced, designed and evaluated; these are named **Collaborative BNS-BU, Layered Collaborative BNS-BU and Splitting of Chunks**. In all mechanisms, the collaboration among the NSPs is defined as an explicit agreement between each other that is followed by the exchange of specific parameters about their preferences concerning remote sources (or NSPs) or parts of the content. The first two approaches **exploit the business relationships between NSPs of either the same or different Tiers in order to rank remote peers effectively**, aiming at the reduction of inter-domain traffic while the users' performance is improved or remains unaffected. Splitting of Chunks is a collaborative approach between **two NSPs that have a peering agreement and wish to exploit the opportunity of jointly reducing the redundancy in the downloading content from non-local users** (or NSPs). The mechanism suggests that the peering NSPs can "share" transit costs by agreeing explicitly to split and download different parts of content through their transit links and then exchange the rest of the parts via their peering link.

All approaches were evaluated by means of simulations. Also their performance was compared to plain BNS-BU, a locality-aware mechanism proposed in the literature, regarding the costly inter-domain traffic and the performance of the peers (measured by download times). The experiments about Collaborative BNS-BU and Layered Collaborative BNS-BU, mainly showed that the collaboration between NSPs that own many customers (other NSPs) and end-users can affect favourably both the inter-domain traffic in the transit links where charging applies and the performance of their own end-users and their customer NSPs. The simulations showed that large NSPs can attain an additional reduction of their costly inter-domain traffic, while in general not deteriorate the performance of their users. However, the effects of the mechanisms to the reduction of the traffic and the download times, depend on the topology and the number of end-users that download the content in each network.

Furthermore, Splitting of Chunks mechanism was evaluated on top of the aforementioned approaches, since they approved beneficial and easily deployable. The main question is whether it is beneficial for peering NSPs to run Splitting of Chunks when they have already adopted locality-based collaboration. The introduction of Splitting of Chunks on top of the aforementioned scenario leads to additional reduction of the transit inter-domain traffic of large NSPs, and maintains user performance, thus leading to a win-no lose situation compared to Collaborative BNS-BU and Layered Collaborative BNS-BU. Also, this mechanism, does not depend on the topology but only on the number of the end-users that download the content.

In general, **large NSPs have the incentives to collaborate with each other. Especially, NSPs that belong to the same geographical location and thus their users probably are interested in the same content may collaborate with each other, creating large clusters, within which they can promote locality without affecting the performance of their users. Such NSPs can further benefit if they provide their customers' NSPs with the incentive to collaborate with them**. NSPs' interest in reducing the inter-domain traffic is motivated by the charges for this type of traffic that are imposed by upper Tier NSPs. These parameters have immediate impact on the performance that the users experience and thus on the reputation of the NSPs. Application service providers and end-users will prefer to adopt the mechanisms in order to benefit from high quality services and/or from specific incentives given by their NSPs such as reduced prices particularly if performance related incentives are also strong.

In the second part of this Ph.D Thesis, we propose and analyse **new coordination schemes as a mechanism that will enable the provision of end-to-end services, which require not only a specific QoS level but also the collaboration of multiple providers**. Such a collaboration is based on the availability of the necessary information among the providers, the way of distributing this information, the way of exchanging and bundling SLAs and the entity that coordinates this bundling (if any. The coordination schemes are classified according to two main criteria. The first criterion concerns the way the information is propagated and schemes are thus classified as Centralized and Distributed. The second criterion concerns the creation time of the offer and schemes are classified as Push and Pull ones. In Push approach the offers are available before a buyer's request while in Pull one the offers are created upon a buyer's request. The combination of those models and the creation of two hybrid ones results in six different schemes. An important aspect of the coordination of the participants is the revelation of information from each of them. There are different alternatives applicable, each of them arising different problems in the framework of QoS. Such information may include the price that the buyer is willing to pay, the costs of the participants and the total number of the providers participating in the chain. Different information sets revealed, affect the total price of the service, the revenue sharing among the participants (affected by means of the prices assigned to their sub-SLA offers) and the selection of the providers that will participate in the chain.

We analyse the information issues that arise in each coordination scheme and we propose ways that can make them equivalent and identify key cases of information availability. Furthermore, we study the problems that the incomplete information causes, through the analysis and assessment of two coordination models, that are representative of them. Based on the assessment of these models, we created guidelines for the choice of the right coordination model in practical cases of cloud and connectivity services markets, depending on the maturity of the respective market and on properties of the demand. For the assessment of the models, we derived rigorously and evaluated numerically the pricing strategies of the providers participating in a value chain to offer a QoS-enabled service between a source and a destination. Each provider was taken as a self-interested entity aiming to maximize its own profits, which of course depend on the other providers' actions. Thus, we formulated the relevant game-theoretic models and carried out equilibrium analysis. In order for our game-theoretic models to be closer to reality, we assumed that the cost of each of the providers for service provision is not known precisely to others, who rather know its distribution. In order for our analysis to be tractable and lead to concrete results, we made a particular assumption on the cost distribution, and focused on the case of paths with three providers, including the source and the destination. It should be noted that many cloud providers, CDNs etc., bring their infrastructure as closer to end-users as possible in order to minimize delays, costs etc. Thus, since we target to such applications, we assume that three providers that may represent an Infrastructure provider, (source of the service), a transit and an access NSP (destination) for the end-user, provide us with a simple, yet very common and important case. The providers' pricing strategies affect the decisions of other providers to interconnect or not as well as the buyer's purchasing decision.

We showed that **the different schemes can be equivalent in terms of pricing strategies. However, in certain schemes, the Distributed Pull and the Distributed Pull coordination schemes, advantageous positions may rise due to the sequential pricing strategies of the participants and to the available information.** In particular, we showed that the first provider (transit) in the value chain, after the buyer, is in an advantageous position comparing to the second one in terms of profits. This advantage is magnified in the Pull coordination schemes. On the other hand, in Push schemes, the advantage of the first provider is substantially reduced, but the scheme loses in efficiency since the probability of the service not being provided increases. Besides assessing the two coordination schemes in terms of efficiency (i.e., probability for the service to be indeed offered), we also compared them with the corresponding ideal collaborative ones, where the NSPs collaborate for the provision of the service, while each just aiming to cover their costs. By means of this comparison, we showed that the **selfish behaviour of NSPs has a significant detrimental effect on buyer's and end-user's satisfaction, while leads specific NSPs**

to an advantageous position against others. However, in a topology where all providers have end-users for such services, and several paths are employed in a long timescale, the highly advantageous position of the first provider of each path is expect to be balanced on the average. Also better knowledge of the market may lead to more successful offers of the service and may suppress the effect of the selfishness of the first price-choosing provider.

The direct result of our business-aware approaches for BitTorrent is the reduction of the costly inter-domain traffic, which is translated to a **reduction of costs** for the NSPs. The gain could compensate the costs for maintenance or upgrade of the network. Thus, **more efficient traffic and network resources management is achieved**. Application Providers and end-users gain in performance or through the incentives that the NSPs provide them in order to adopt the mechanisms. Furthermore, our coordination schemes enable the provision of end-to-end QoS enabled services. In such schemes, NSPs can collaborate also with Application Providers or Cloud Providers. These collaborations allow the **provision of new services, increasing the profits of NSPs and other providers of the value chain, as well as their reputation and their customer base**. Being able to reach more customers even further with an assured QoS level gives providers the opportunity to **form larger customer bases and of course attain increased profits**. In general, provisioning new services or existing ones with less charges, which allow them to increase their profits or reduce their retail prices or both, and/or higher quality foster the competition. Users can only benefit from the **variety of services, the variety of the content in high quality and the competitive pricing**.

Contribution:

1. Effective business relation- aware approaches that distinguish among non-local resources for P2P applications (BitTorrent specific):
   (a) Collaborative BNS-BU and Layered Collaborative BNS-BU:
   Both exploit the business relationships between NSPs of either the same or different Tiers in order to rank remote peers effectively
   (b) Splitting of Chunks:
   Jointly reduction of redundant content from remote NSPs by two peering NSPs
2. New coordination schemes that enable the provision of end-to-end services with a certain QoS level by the creation of bundled SLAs:
   (a) Analysis and assessment of information distribution issues in two coordination schemes.
   (b) Guidelines for the choice of the right coordination scheme in cloud and connectivity services markets.

Conclusions:

1. Large NSPs have the incentives to collaborate with each other in P2P traffic management, creating large clusters, preferably geographical ones, within which they promote locality without affecting the performance of their users, while they can further benefit if they provide their customers' NSPs with the incentive to collaborate with them.

2. the different schemes can be equivalent in terms of pricing strategies. However, in certain schemes, the Distributed Pull and the Distributed Pull coordination schemes, advantageous positions may rise due to the sequential pricing strategies of the participants and to the available information. Also, selfishness of NSPs has a significant detrimental effect on buyer's and end-user's satisfaction, while leads specific NSPs in an advantageous position against others. Large markets where customers exist along the whole path create symmetrical topologies that minimize the advantageous position of the first provider.

Impact on Society:

For the NSPs: reduction of costs, more efficient traffic and network resources management, provision of new services, increased profits, reputation and customer base

For Cloud Providers, CDNs, Application providers: provision of new services, increased profits, reputation and customer base

For end users: variety of services, variety of the content, high quality services/content, competitive pricing

1.4 Outline

The rest of the document is organized in four more Chapters. In the second Chapter (Chapter 2), we present the background knowledge and the related work that has already been carried out in both locality-aware mechanisms and SLA negotiation and pricing strategies. In the third Chapter (Chapter 3) we present the analysis of the collaborative mechanisms for BitTorrent protocol, as well as the results of the simulation experiments. Likewise, in the fourth Chapter (Chapter 4) we introduce the coordination models and the information issues involved, and we analyze two representative models. Last, in the fifth Chapter (Chapter 5) we present our conclusions and some directions for future work.

Chapter 2

Background Knowledge and Related Work

2.1 Background Knowledge

Internet consists of both smaller and larger networks that interconnect with each other. These networks have their own policies, services and target customers. The interconnection of all of them is achieved by the use of IP addressing and the BGP routing protocol. Generally, depending on the size and the inter-connections with other networks, they are classified into three tiers; Tier 1 for larger networks, Tier 2 and Tier 3 for smaller networks (usually providing only access).

Service Providers. In each Tier different service providers may exist. An NSP sells direct Internet backbone access, usually to big companies or other customer providers. Also, they may be telecommunications companies, Internet service providers or cable television operators. An Internet Service Provider(ISP) offers access to the Internet but usually to end-users. Also, they may not provide only Internet access but domain name registration and hosting, dial-up access and leased line access as well. We will use those two terms as identical since this directly does not affect our analysis. Furthermore, we can categorize those providers into transit that transfer bits for other providers (which are usually their customer providers) or edge (access) ones that contact the end-user. Of course, a transit provider can have end-users. In our work the transit providers belong to Tier 1 or Tier 2, while access providers to Tier 3, as analysed below.

Except for network access, other services may include Application providers, such as content distribution providers and Cloud Computing. A Content Distribution Network (CDN) serves content to end-users, providing high availability and performance. The role of a CDN operator can be played by an ISP or NSP and of course by any special business entity such as Akamai. Cloud Computing providers [8], [9] can be further categorized into Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS) providers. IaaS offer virtual machines on-demand from their large pools installed in their data centers. PaaS providers deliver a computing platform with an operating system, a programming language execution environment, a database, or a web server. SaaS providers operate application software in the Cloud, which can be used by end-users, usually on a pay-per use basis.

Internet Tiers. Tier 1 NSPs interconnect with each other via private peering agreements, to have their traffic delivered without paying. Usually they have their own large Internet backbones with international coverage and support large traffic volumes, large customer bases, and large numbers of routers. They may peer with other Tier 1 NSPs on more than one continent. Tier 2 NSPs are able to provide service to customers on more than two continents, but usually they have smaller networks than Tier 1 NSPs. They buy their connectivity to Internet from Tier 1 NSPs. Tier 3 NSPs focus on local retail and consumer markets. They are customers of higher-Tier NSPs for access to the rest of the Internet [10].

Transit Business Relations. As mentioned before, smaller networks pay larger ones to gain access to the rest of the Internet. This service is called Internet Transit (or transit) and is the business relationship whereby an NSP sells access to the global Internet. Higher Tier NSPs are transit providers, i.e., sell transit to smaller NSPs. Except for a physical connection, the transit agreement allows the customer to announce its routes to the rest of the Internet and at the same time the Internet routes, advertised by other NSPs, to be announced to the cus-

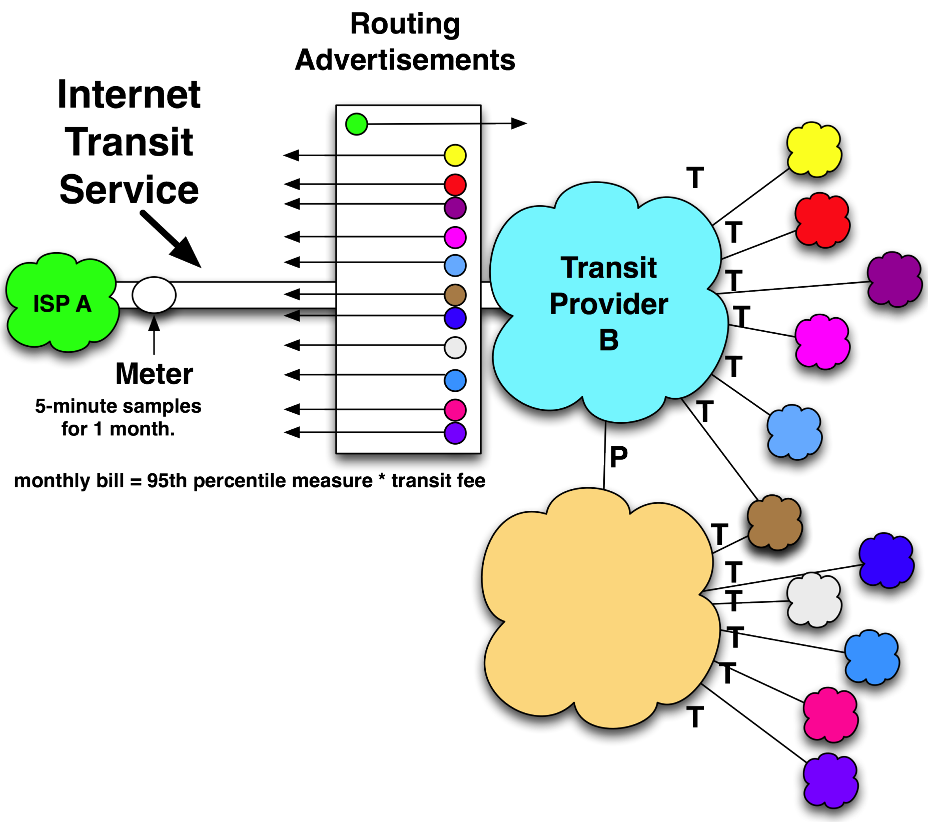

Figure 2.1: Transit Service

tomer. In Figure 2.1[1], a transit agreement is illustrated. NSP A (or ISP - taken as identical for our work) purchases transit service from B and announces his destinations. Transit Provider B in his turn announces to NSP A the routes to reach the entire Internet (shown as many shaded small networks to the right of the Transit Providers). For this service NSP A pays specific charges to B.

Transit Pricing Scheme. The transit service is charged using the 95th percentile traffic sampling technique. This method comprises three steps, which are shown in Figure 2.2[2]. First, every five minutes the meter on the service is sampled in both directions (in and out). Between two adjacent samples their difference is calculated and stored. Then, at the end of the month, the five-minute deltas

[1]Source: [11]
[2]Source: [11]

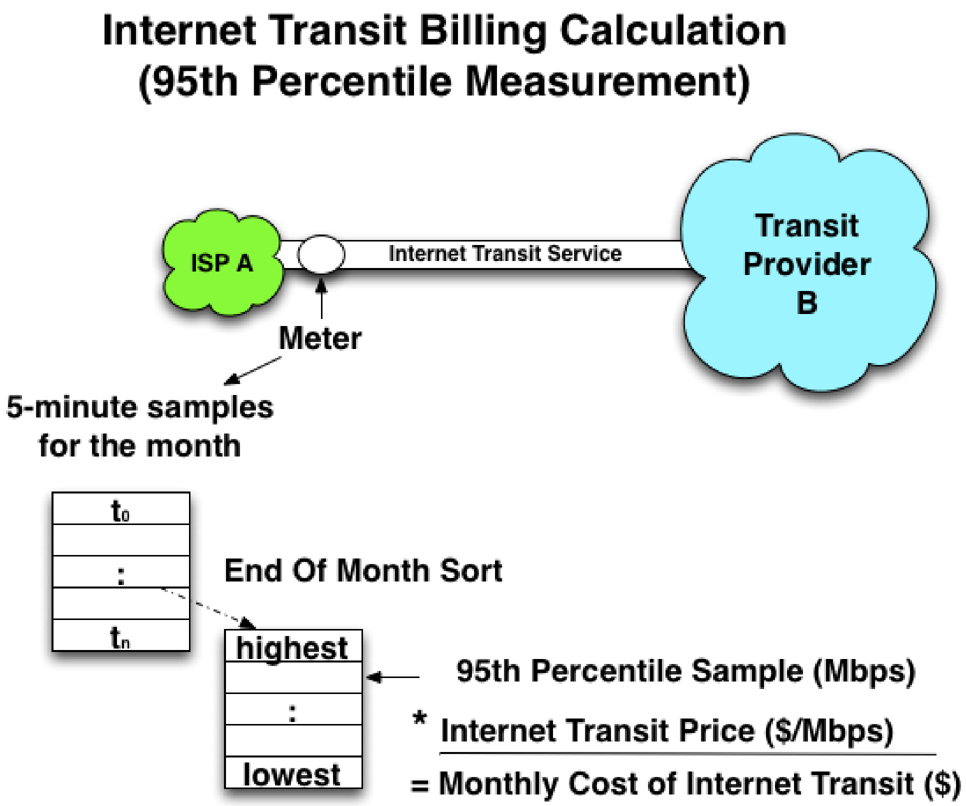

Figure 2.2: 95th Percentile Measurement Method

are sorted and the 95th percentile is used to calculate the traffic volume for the month. The charges may be proportional to the 95th percentile of either the inbound traffic, the outbound, their sum or the maximum one. In our work we use the maximum of the 95th percentiles of the inbound and outbound traffic as shown in the next equation.

$$MonthlyBill = max(inAt95th\%, outAt95th\%) * InternetTransitUnitPrice$$

Peering Business Relations. In order to minimize the costs of transit traffic NSPs of roughly the same size establish peering business relations in pairs whereby the companies reciprocally provide access to each others' customers. Peering is typically a free arrangement and it is based on the pre-assumption that the peering NSPs exchange roughly the same traffic amount. Whenever this is not the case, or when it is not, one of the parties usually pays the other. This

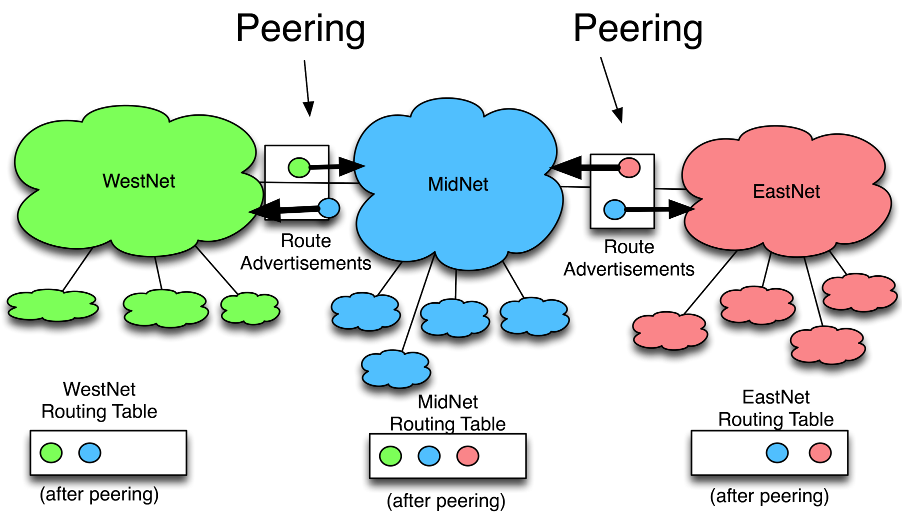

Figure 2.3: Peering Business Relation

is called Paid Peering. Peering agreements do not work as transit ones in the case of address announcements. As shown in Figure 2.3[1] MidNet, which has peering agreements with both EastNet and WestNet, does not announce the destinations of WestNet to EastNet or the other way. The traffic must be initiated from customer NSPs or end-users of one NPS and destined to the other's customers or end-users. Also, note here that Tier 1 NSPs have only peering agreements with each other (and no transit).

Service Level Agreements. A Service Level Agreement (SLA) is a contract between a service provider and a customer, which may also be another service provider. Based on this contract, both sides specify their obligations to each other, as well as the penalties in case that those obligations are not met. Between two NSPs the SLA can be translated into transit or peering agreements. In case of QoS assurance, SLAs provide the requirements of the agreed level. The information contained in an SLA may include a description of the nature of the service to be provided and the expected performance level of the service, including usually its reliability and responsiveness. For example, the expected performance level can be translated into specific throughput of the line or minimum traffic

[1]Source: [11]

exchanged and/or specific QoS requirements. Also, the SLA may include information about the procedure for reporting problems and the time-frame for response and problem resolution [12].

In the market today, the negotiation of the SLAs is bilateral, meaning between two parties. We will focus on the negotiation of two or more NSPs for the provision of a bundled SLA. Thus, until the negotiations are over we need two types of SLAs, i.e., the SLA offers and the Network Capabilities [13]. Both of them are SLAs provided by an NSP and constitute candidates for part of the bundled SLA. Their main difference is that SLA offers contain also a specific price for the service described, while Network Capabilities may only contain an indicative price, which may change. In other words, SLA offers are ready to purchase SLAs and the NSPs must be able to provide the service. For Network Capabilities this is not the case. Those SLAs are just an indication of what the NSP is able and willing to provide but by the time of the purchase request some of these service characteristics may have been modified.

Overlay Networks and Applications. An overlay network is built on top of the physical network. The overlay nodes are connected with each other by logical links that may correspond to physical paths of the underling network. Overlay applications are those applications that create or make use of overlay networks, such as P2P Filesharing or Cloud Computing. In P2P applications, the overlay networks that are created by the peers that connect with each other, are agnostic of the physical network or take account of certain characteristics that are inherent to them, e.g., those relating to P2P performance. This gives rise to significant problems to the NSPs, since they cannot predict and manage their traffic in a way that the inter-domain costs can be controlled. In our work, we initially focus on P2P Filesharing applications and especially on the most popular one namely BitTorrent. Furthermore, we focus on overlay applications that may need the creation of an overlay network with extra guarantees that the physical network cannot provide, such as Cloud Computing or Real-Time Entertainment. These extra guarantees are translated into QoS requirements that the overlay network must provide to the application, and form the aforementioned SLAs.

2.2 Related work on Locality-awareness

2.2.1 BitTorrent

BitTorrent is a P2P file sharing protocol, designed by Bram Cohen in April 2001 and is used to distribute large amount of data over the Internet [14]. Since it is a P2P protocol, the users may simultaneously download content from a large number of other users and concurrently upload to each other. This way, many users can share a file without facing the scalability problems of a client-server architecture. However, BitTorrent differs from other P2P protocols, since it operates based on a central entity, the *tracker*, as well as on a fairness principle, referred as *tit-for-tat*. The tracker "holds" all the peers that are willing to download the same file even if they have just connected to the so called swarm. Thus, the peers either own only a part of it or the whole file. Also, a user can download simultaneously different pieces of the same file from multiple users, reducing this way the download time that they are experiencing. Tit-for-tat is a reciprocation principle that solves the problem of free riders, i.e., users that download content without uploading. According to this principle, in order for a user to download the file, he must also upload some parts of it to other users, with the uploading speed attained to a user being closely related to the possibility of downloading from him part of the content.

Below we present in detail how BitTorrent works, introducing also the respective terminology. Let us assume that a user owns a file (content) that wishes to distribute to others. Since it has the whole file, this user is called *seeder*. The owner creates a small *torrent* file that contains metadata about the file to be distributed, such as its name, size, number of pieces, piece length etc. Also it contains the URL(s) of the tracker(s). A tracker, as already mentioned, is a server that provides information about the participants in a *swarm*, i.e. all peers (including seeders) sharing the same file. The torrent file is uploaded to a web site from where it can be accessed by any interested user. Let us now assume that a new user wants to download the specific file. Via the web site and the torrent file, the new user (now called peer), reaches the tracker(s) and learns the IP addresses of a part of the peers participating in the swarm. Such peers may be seeders or *leechers*, i.e., those that have only a portion of the file yet. After obtaining a list of other peers in the swarm, the new one establishes connections with a subset of the peers which now are considered as his overlay neighbours. These neighbours send him which pieces of the file, referred to as *chunks*, they already have. The peer knows from the tracker the total number of chunks of the file. With this information available he finds the rarest (usually) chunk among those available to all of his neighbours and request it from those who have it. Eventually one of them will *unchoke* him, i.e., start upload to him. When the peer acquires his first chunk, he starts to upload it to a subset of his neighbours that expressed their interest to it. The neighbours that the peer is uploading to, at a certain time, are called *unchoked* peers [14]. The peer continues to download chunks from a number k of his neighbours simultaneously, the exact value of k depends on the implementation and is usually 4 or 5.

Next we focus on certain parts of the aforementioned mechanism that are of particular interest for our research. The first step that each peer makes, is *Neighbours Selection*. The list of peers obtained from the tracker, is not sorted under any terms. Also the peer chooses randomly which of the peers in this list will be his neighbours. After establishing his connections, the neighbours inform the peer about the chunks that they have available. This is done periodically and each peer follows the same procedure (informing his neighbours about the chunks he has) after obtaining his first chunk. The peer declares if he is interested or not in downloading any of the chunks the neighbour has. This operation allows the neighbours to mark the peer as a potential one to be unchoked.

The *Unchoking Algorithm* determines the distribution of the content and the avoidance of free riding. In fact, leechers continue to upload to other leechers from whom they can download fast, according to the tit-for-tat reciprocation principle. As mentioned before, the neighbors that are already receiving content from a specific peer referred as unchoked by this peer, while these that they do not receive (but they are still interested) are called *choked*. Every 10 sec a peer unchokes a default number of 4 of his interested neighbors; this may differ to other implementations. If the peer is a leecher, he unchokes them based on the highest of the download rates of receiving data from them. This strategy (i.e, tit-for-tat) provides an incentive to a peer to upload content to others and with a high rate if possible. In case he is a seeder, these 4 neighbours are those which were most recently unchoked [15]. In order to support newly joined peers in the swarm and the discovery of new resources, every 30 sec the peers unchoke randomly an interested neighbour (the fifth one) giving him the opportunity to download chunks. This is called *Optimistic Unchoking*. Apart from assisting new entrants and avoid their starvation, this algorithm allows the peers to explore and find new resources, i.e, upload bandwidth. In the seeder mode, this algorithm ensures that the peer with the longest unchoking time will eventually be choked by the seeder thus allowing new peers to be unchoked [15].

After being unchoked by a neighbour, a peer has to declare to him the chunks that he is interested in. There are several existing strategies for deciding which chunks to ask first. According to the *Piece Downloading Strategy*, the clients choose to download chunks randomly. A better strategy is the *Rarest First*, in which a peer can determine which chunk is rarest by keeping the initial bitfield, indicating chunk availability by each neighbour and update them every time he receives a message with information regarding the available chunks [14]. Then he just finds the rarest chunk and asks for it. A strategy serving a different purpose is the *End Game Strategy*, in which the peer asks from all of his neighbours his missing chunks, if he is close to finishing the file download.

2.2.2 Locality-awareness mechanisms

Extensive research work has already been carried out in the literature on the promotion of **locality and proximity** in P2P networks that aims at reducing the inter-domain traffic, which imposing high costs to the NSPs. In particular, with promoting locality the NSPs achieve to keep the traffic in their network by assisting their peers to find local resources. Proximity, which is defined by the number of BGP hops that separate the source from the destination, is promoted in order to reduce the delays that are introduced when traffic is trespassed multiple networks. In this section we present an overview of proposals for locality-awareness mechanisms as well as research work that indicates issues arising from these mechanisms that provided an extra motivation for our work.

Bindal et al. [16] in their Biased Neighbor Selection (BNS) algorithm presume that a peer can be provided with a biased list of peers to connect to. Most of the peers in this list belong to the same network as the peer that requests the list from the tracker. The simulation results over 14 different ASes showed that the transit inter-domain traffic is reduced significantly, while the download times of the peers are not influenced much, although some deterioration of performance was indeed observed.

Aggrawal et al. propose an Oracle service hosted by the ISPs in order for them to cooperate with P2P users [17]. The Oracle ranks a list of potential neighbors based on locality (same AS) and proximity (AS hops distance). The evaluation results showed that the properties of the overlay topologies, such as small diameter, small mean path lengths and node degree are not affected by the use of the oracle service, while at the same time the network locality increases.

A similar approach where again an overlay entity called iTracker communicates either with the peers or with application trackers providing them information about the underlay, was developed by P4P project [18]. The simulations in PlanetLab and real networks showed a reduction in transit inter-domain traffic and download times as well.

A different implementation of the same idea is presented by Choffnes and Bustamante in [19]. Biased neighbor selection is based on the information that is collected from DNS lookups on popular CDNs names. The similarity of the lookups of two peers determines their level of proximity.

In [20], Piatek et al. present three pitfalls to ISP-friendly P2P design. One of them concerns the conflicting interest that different Tier ISPs have while inter-domain traffic is reduced causing less costs for some and less revenues for others.

Wang et al. in [21] examine the different contents and peer properties in regards to the locality issues. They conclude that the peers belonging to a few large AS clusters are more eligible to be affected by a locality mechanism; thus, a selective locality mechanism is more promising to optimize the overhead and the robustness of BitTorrent.

Oechsner et al. propose in [22] a new algorithm, referred to as Biased Unchoking (BU) and they combine it with the aforementioned BNS algorithm (BNS-BU). BU influences, based on the ranked list received from a tracker, the optimistic unchoking algorithm of a peer that indicates to which neighbor to upload. The experimental evaluation and comparison of plain BitTorrent, BNS, BU and BNS-BU in [22] showed that the two complementary mechanisms should be used together in order to achieve better performance in terms of transit inter-domain traffic while the performance of the peers remains unaffected.

SmoothIT project [23] implemented the BNS-BU mechanisms under a different perspective. One of the key objectives of the project was to apply specialized economic theory for building in a fully decentralized way network efficient Internet-based overlay services in multi-domain scenarios, solving the information asymmetry problem. Also, in SmoothIT the necessary networking infrastructure and their components for an efficient implementation of such economic traffic management mechanisms were designed, prototyped, and validated in an IP testbed and trial network. One of those key network components was the SmoothIT Information Service (SIS) entity, which ranks the peers of the trackers' lists according to BGP router data. This implementation called BGP Locality Awarness Economic Traffic Management (ETM), uses BGP router data to rate potential neighbors according to their BGP routing distance to the local, querying peer. To this end, metrics like the AS hop distance and the local preference value are used. This rating used by the BNS, BU mechanisms implemented in the client. The evaluation shows that BGPLoc can save large amounts of inter-AS traffic if the number of peers in the same AS is large enough to allow for the preference of local neighbors to be significant and effective. It is less effective, but still saves traffic, in small ASes. The largest amount of traffic savings is possible under high load conditions, and when a large local peer population exists. Regarding end users, BGPLoc introduces unfairness in the download times of the peers, since peers in small ASes take longer to download the file. Thus, with BGPLoc in its pure form, there is no clear win situation for all end users in scenarios with the access network as a bottleneck.

Lehrieder et al. in [24] investigate the way BNS and BU mechanisms affect the performance of the users. For scenarios with homogeneous peer distributions and all peers having the same access speed a win-no lose situation arises, i.e. reduction of transit inter-domain traffic-no deterioration of performance of users. Changing the percentage of local peers used for either BNS or BU, they argue that the actual impact for a specific peer depends heavily on that percentage as well as the topology used.

2.3 Related work on QoS

Extensive research work based on game-theoretic models, has been done in the literature concerning the provision of QoS-enabled services [1]. The works most related to ours are presented in this Section. Part of this work concerns the lack of QoS-enabled services in the market. Akerlof in [25] relates this lack to the market statistics that judge the quality of a certain good. Thus, there is an incentive to the sellers to market poor quality goods, since the returns for good quality have a repercussion to the entire group whose statistic is affected, rather than to the individual seller. Musacchio et al. in [26] suggests that it is due to the lack of commercial incentives for NSPs to enable quality-assured services, as the fruits of such investments go to content providers only.

Several game theoretic models study the interactions among the players for the provision of QoS-enabled services. Cremer et al. in [27] provides concrete proofs of the strategies played by the large NSPs in various scenarios of competition and suggests that NSPs with larger installed bases have a strategic motivation for degrading the quality of interconnection. [28] argues that substantial benefits of an upgrade to a network are brought to less well-provisioned networks due to their interconnection with the former. Hence, the networks may end up in adopting a free riding strategy and be extremely reluctant to invest. These articles mainly focus on the lack of motivation of the NSPs to adopt QoS. However, note that the emergence of new applications in the market will increase the need of end-to-end QoS connectivity.

Furthermore, various models have been proposed for the study of the whole market of QoS, including the users. Zhang et al. in [29] a simple economic model is developed to study the interactions and the competition among service providers, network providers and users. The authors do not include quality in their economic models, but they define service and network upgrade as an increase in quality. Despite its simplicity, this economic model captures the complex relationships

[1]Note that we do not address literature on QoS technologies, only on models that study the interactions among the players involved

among different participants of the value chain of the Internet market. Yet the authors of [29] consider neither the problem of end-to-end connectivity nor the interconnection problems between NSPs.

Closer to our work is that of Walrand in [30]. The formulation of the problem therein is similar to ours. In particular, a group of interconnected providers offer a bundled service and share the revenues. Each provider maximizes its own profit while maintaining the service performance. The demand of the users is affected by the total price. The authors show that through a non-cooperative pricing strategy, where each provider chooses independently to maximize its own profit, a Nash equilibrium with an unfair distribution of profits may prevail, with the bottleneck provider being in an advantageous position, which may even discourage future upgrades to the network. They also analyze a fair revenue-sharing policy based on weighted-proportional fairness. One of the main differences of our work with [30] is that we investigate the profits of the NSPs in the chain under the assumption of less precise cost-related information. In particular, we consider that the cost of each of the NSPs is not known to the other players, who rather know the cost distributions. In [30] the costs are taken as known to the NSPs. Also, contrary to [30] where the prices are chosen simultaneously, we study cascading models, where NSPs choose their prices in a particular order, which pertain to Stackelberg game-models. Finally, we do not assume that the demand of the buyer w.r.t. the "quantity" of the service, is affected by the price of the NSPs, but rather that the buyer has two choices, either purchase a "unit" of the service if its price is acceptable for the buyer, or otherwise decline. In fact, in one of our models, the NSPs know the buyer's offered price in advance and select their prices accordingly, which is not the case in [30]. In [31], Aguiar et al. analyse the impact to the organization of the Internet of a distributed cascade model for forming and pricing connectivity SLAs, with multiple possible paths from a source to a destination. They analyze the Nash equilibria in terms of choosing the coefficient involved in these strategies. The authors of [31] also assume that neither the cost of each NSP nor their peering partners is known, and they introduce competition among NSPs. However, they take into consideration neither the willingness to pay of buyer of a service, nor pricing by the last NSP in the chain. In our model, contrary to [31], the two edge NSPs participate in the decision of forming the offer of the service, either knowing the buyer's offered price or having to take into account the probability of the service offer to be rejected due to being priced excessively for the buyer. On the other hand, in our work, we do not consider competition. In [32], Amigo et al. propose a framework for distributed network bandwidth allocation with QoS constraints. Also, they employ network bandwidth auctions for selling quality assured paths and then they develop a mechanism for performing the revenue sharing of a federation, based on Shapley value. The authors of [32] focus more on the allocation of the QoS constraints and revenues while we focus on whether the service is offered depending on the total price as formed by the individual pricing strategies of the NSPs.

Chapter 3

Collaboration For P2P Traffic Optimization Over Inter-domain Links

3.1 Motivation of P2P Traffic Optimization

P2P Filesharing is an alternative way of the traditional client-server file downloading. All users that own the same file are called peers and belong to a swarm. A new user entering the swarm locates the other peers and requests from all of them at the same time, the file, which is split to small parts called chunks to ease this process. From all P2P protocols, the largest amount of traffic is produced by BitTorrent, which has risen in volume by over 40% during 2012 [1]. In fact, P2P was more popular some years ago (when this research work began). According to Ipoque studies [4], in 2008, P2P generated 43 to 70% of all traffic in the Internet. BitTorrent had the biggest share of this traffic, about 80%. Nowadays, it only produces a 10.31% of total peak traffic ([1]), which however, is not enough to remove it from the first position of the top 10 applications used in Europe at peak period time.

The growth of the popularity of P2P applications resulted in an increase on the revenue of ISPs and in the rapid and constant upgrade of their regional backbones and speeds, due to the increasing demand for higher access rates. However, the fact that the overlay applications exchange their traffic through logical overlay connections creates a significant problem for ISPs. Logical connections are usually agnostic to the physical structure of the Internet. The peers choose their download resources based on overlay parameters and application objectives, such as upload speed, or even randomly. This imposes traffic engineering difficulties and high costs to the ISPs due to inter-domain traffic. As a result, some ISPs prefer to even shut down P2P connections whose other end is outside their Autonomous System (AS) [33] or throttle their bandwidth. However, such measures may result in unsatisfied customers and thus in a decrease in the ISP's income. Such a case was that of Comcast in 2007. Its subscribers claimed that the company was interfering with their use of peer-to-peer networking applications. The Commission believed that Comcast had "several available options it could use to manage network traffic without discriminating" against peer-to-peer communications and ordered the company to disclose details of a new bandwidth demand management system that it had already adopted in between [34].

As the restriction of the P2P traffic is not a viable solution, extensive research work has been carried out aiming at the reduction of the inter-domain traffic and, consequently, of the associated costs of the ISPs. This work yielded to overlay traffic management techniques that are successful from the ISP's point of view since they increase the level of locality of the traffic. For a detailed review of the literature see section 2.2. However, at the same time it is desirable that the performance experienced by users remains unaffected or even improves. This gives the incentive to the Application providers and end-users to adopt the mechanisms in order to benefit from high quality services and/or from specific incentives given by their NSPs such as reduced prices particularly if performance related incentives are also strong. The peers considered as local are those that belong to the same AS, where the traffic exchanging between them passes no inter-domain links. Respectively, we define locality, which is often promoted as follows: ISPs provide, usually through an overlay entity (that acts like a server) residing in their AS, information about the physical topology of the Internet to the overlay application. This is done by ranking (by the overlay entity) the peers participating in the swarm according to metrics such as: a) whether they reside in or outside the AS (locality awareness) and b) the number of AS hops according to the BGP path (proximity) as done in SmoothIT project [23] (see also section 2.2). In our work, we assume that the information that this overlay server provides is a list of peers ranked according to locality and to distance in term of AS hops; this ranked list is then fed back to the peer requested it. Note here that the peers request the local overlay server to rank all (or a portion of) other peers in the swarm. However, the main locality promotion approaches do not distinguish non-local peers according to the business relations of their ISPs.

In fact, ISPs inter-connect with each other by means of bilateral agreements (SLAs) to allow the provision of connectivity services of the Internet. Such contractual business agreements for exchanging traffic directly between the ISPs, are classified as customer-provider connectivity and peering connectivity [24], [19], [35]. In customer-provider or else transit connectivity, as discussed in Chapter 2, one AS (provider or transit AS) provides the other (customer) with transit Internet access for a fee, which depends on statistical metrics of the inter-domain traffic, such as the 95th percentile calculated on a monthly basis. In peering connectivity the two ASes interconnect with each other, and exchange traffic originating in one of the ASes and destined to the other; this is done for free, as long as the volume of traffic in the two directions is symmetric or almost so. Thus, the two peering ASes have a mutual benefit by eliminating the charges of exchanging their traffic through transit links and sharing the costs of their inter link. These terms have already been defined in Chapter 2. Peering agreements are one way of collaboration between pairs of ISPs for reducing their inter-domain costs. We are based on those peering agreements to promote further collaboration between pairs of ISPs.

The locality-Aware peer selection algorithms, namely Biased Neighbor Selection (BNS) and Biased Unchoking (BU), as they are presented in [17] and [16] are able to distinguish the local peers belonging to the same AS (from a specific peer view) from the remote ones. They rank the peers according to this information and also to whether they belong to a peering AS, as proposed by the EU-funded project SmoothIT [23]. In our work, we build on those approaches, since neither of them nor others already discussed in Chapter 2 distinguish non-local peers according to the business relationships [33] among the ISPs. In our opinion, such a distinction is very important, because it is expected to lead to a significant reduction of the transit inter-domain traffic where charging applies. As will be seen later, this is indeed the case.

The specific Locality-Aware BitTorrent peer selection algorithm employed by SmoothIT is based on a combination of Biased Neighbor Selection (BNS) and Biased Unchoking (BU), as presented in [16] and [22], and has already been evaluated successfully for a wide variety of simulated scenarios. We introduce an innovative variation to this that employs the notion of interconnection agreements in the ranking method of the peers that is used by BNS and BU. Our objective is to investigate the benefits of employing this information for the ISPs and the peers. Moreover, we introduce and evaluate an innovative traffic management approach on top of the locality-awareness techniques that also exploits the business relationships though in a different way. This approach referred to as Splitting of Chunks, aims to avoid the download of redundant (duplicate) content via the costly inter-domain links, while allowing more traffic to be exchanged through the peering links. Splitting of Chunks represents the "ultimate" way for ISPs to collaborate in order to reduce traffic redundancy in the charged transit links, which motivates our studying it. We present the specification of the BNS-BU algorithms that are based on the agreements of the ISPs (Collaborative BNS-BU approaches) and the Splitting of Chunks approach and we compare their performance to the standard SmoothIT BNS-BU algorithm (plain BNS-BU hereafter).

3.2 Details in Locality-aware mechanisms

Locality-aware mechanisms have already been developed in order to assist peers to download from local or "closer" to them (in terms of hops) neighbours. In this section we will present in detail the two most significant algorithms, named Biased Neighbour Selection (BNS) and Biased Unchoking (BU), on top of which we have built our work; an outline of them was already provided in Section 2.2.

3.2.1 Overlay Server

Both algorithms are based on an overlay server as also in [23], called SIS (see Section 2.2, [23]), which informs the overlay application about the locality of the peers participating in the swarm. This server resides in each AS and accepts from local peers, lists with peers acquired from a tracker. Its main role is to rank those peers in the list according to locality (same AS with the requesting peer, i.e. local ones), peering agreements and proximity (AS hops away from requesting peer's AS). While locality is used to reduce inter-domain traffic, proximity is used for performance, since further ASes usually indicate more delays. Based on this ranked list, the peers will run BNS and BU mechanisms in order to connect and upload content to the most preferred other peers in the swarm. This way locality is promoted and the traffic in the inter-domain links is reduced. Thus, the overlay server maps a specific value to every local peer, forming the highest priority or 1st-value group and another, smaller, value to every peer that belongs to the peering ASes, forming the 2nd-value group. The rest of the peers are ranked according to the proximity of their ASes based on BGP hops. More AS hops mean that the peers belong to smaller-value groups. In Figure 3.1 a simple topology is depicted. There are four ASes (A, B, C, D). The solid lines indicate transit inter-domain links for which charges apply. In the upper Tier in this case belong ASes A and B. Thus, C is charged by A for the traffic that passes through the link connecting them. On the other hand, the dashed lines correspond to inter-domain links that charges are not applied due to peering agreements between the ISPs. There are peers in each AS, while a new peer (red) is connected to the swarm in AS C. In AS C there is an overlay server that will rank the available peers for this new peer, forming the different groups. In each group the remote peers are marked with the same value. Thus, the peers that belong to the same AS as the new peer (AS C) form the 1st group. The 2nd group is formed by the peers in the peering AS (AS D). Then, the 3rd group is formed by peers in AS A, who are only one hop away from the new peer, while the 4th by those in AS B, who are two hops away from AS C.

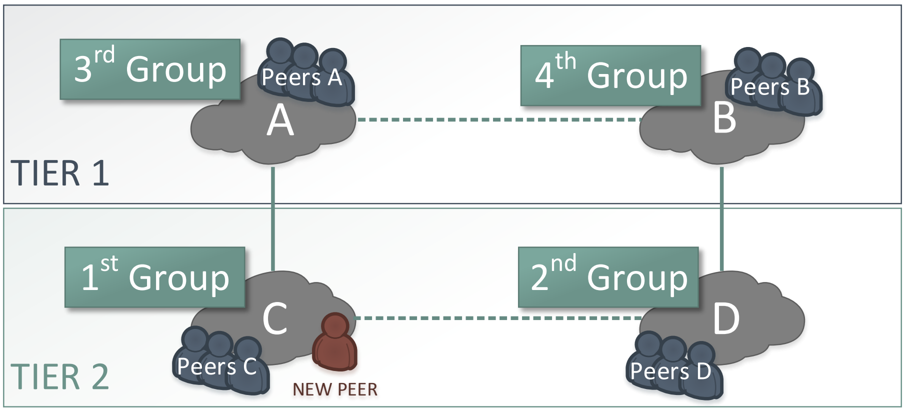

Figure 3.1: Groups formed by Overlay Server

3.2.2 Biased Neighbor Selection (BNS)

This algorithm intervenes in the way Neighbours Selection is done. The peer does not connect to a random subset of the peers in his list of neighbors, as in plain BitTorrent but rather he first establishes connections with peers that belong to the same AS.

BNS enables a peer that had already received a ranked list from the overlay server to connect to the most preferable peers. In our implementation, as also implemented in [22], 90% of a peer's neighbours are chosen based on their ranking. The peer sorts the list according to the rankings and starts connections from the highest values to the smallest ones until he reaches the threshold of 90% of maximum the neighbours that he may have. After reaching 90% of the connections, he randomly chooses the remaining neighbours from the rest of the groups.

3.2.3 Biased Unchoking Algorithm

Biased Unchoking Algorithm (BU) refers to a variation of the optimistic unchoking mechanism that BitTorrent uses. We remind to the reader that each peer unchokes those of his neighbours that upload to him with the highest speed. He also unchokes one random neighbour, and this is what is referred to as optimistic unchoking.

The optimistic unchoking slots of a peer in BitTorrent are limited. Biased Unchoking influences the random selection of neighbours that will be unchoked and eventually get the content. The authors in [22] rely on the fact that the choke algorithm has a major impact on which peers exchange data. In BitTorrent, if the number of local neighbours is small then the possibility that a peer exchanges data with a remote neighbour is greater than with a local one. Biased Unchoking boosts the function of BNS by interfering to the Unchoking Algorithm. The peer chooses to unchoke optimistically those of his neighbours that are interested to the chunks that he has already available, using the ranked list provided by the SIS. He prefers to unchoke randomly a neighbour from the highest-value group, i.e, that belongs to the same AS, according to the metrics that obtained from the ranked list. If this group is empty, he can choose from the next highest-value group etc.

3.2.4 BNS-BU

By combining both algorithms, the locality is enforced first when choosing the neighbours and then again when unchoking one of them. Thus, even if a peer has connected to a remote neighbour, due to lack of local ones for example, he will prefer to unchoke one optimistically “closer" to him. We will use the combination of those two algorithms in our work, since their simultaneous use results in a major reduction in inter-domain traffic, as presented in [22].

3.3 Business-aware mechanisms

3.3.1 Problem Identification

For the reduction on inter-domain costs imposed by the transit agreements, ISPs resort to the establishment of peering agreements. This is a form of collaboration of ISPs. In our work we focus on the use of this basic form of collaboration, which corresponds to a business relation of the ISPs, for ranking the remote peers in order to further promote locality and proximity. We focus on pushing further the collaboration of the peering ISPs based on that first collaboration that

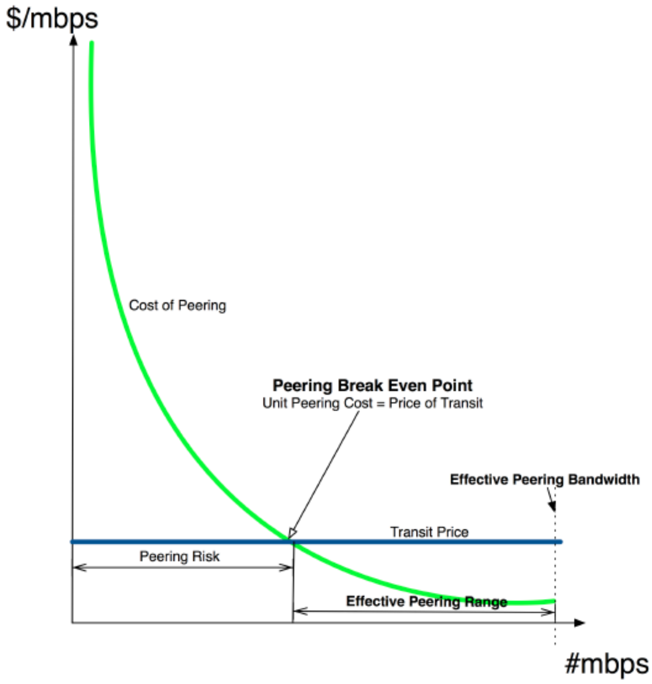

Figure 3.2: Peering VS Transit

they have in order to reduce more their inter-domain costs, without affecting the performance that the users are experiencing. Under our approach, the peering-link traffic, of course, is increased but this is rather good since, as shown in Figure 3.2[1], the more Mbps pass through the link the more effective the peering for the two ISPs. Of course, we assume that since these ISPs already have a peering agreement, the line "Cost of Peering" is below the one "Transit Price" for the traffic typically exchanged by them.

In particular, we propose the modification of the BNS-BU approach in such a way that takes into consideration the business relationships of the ISPs in ranking the peers received from the tracker, upon such a request. As mentioned before, the overlay server ranks the remote peers and returns this ranked list to the requesting peers. In particular, the overlay entity returns to the requesting peer a pair of values i.e. (*remote peer IP address*, *remote peer group value*) (a, g), one for each peer in the list. Thus, the requesting peer uses g to identify the group to which another peer belongs. The overlay entity will assign the highest g to local

[1]Source: [11]

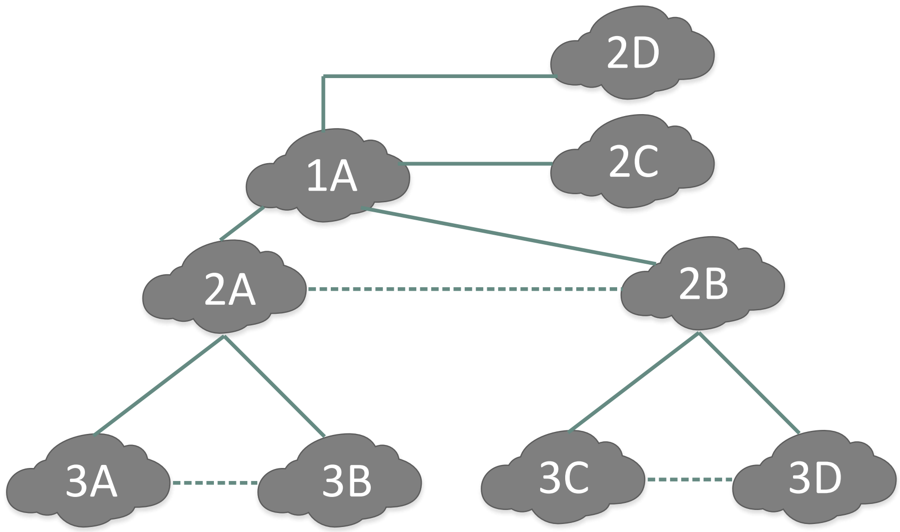

Figure 3.3: Example Topology

peers (relatively to the requesting peer), the second higher g to peers from the peering AS(es) and then classifies the rest of the peers according to BGP hops; more hops away means smaller values and hence less priority.

Nevertheless, if two ASes are the same number of hops away, this does not necessarily indicates that the exchange of traffic with each one of them will cost the same. To explain this, we introduce the sample topology depicted in Figure 3.3. There are three Tiers of ISPs. Each Tier is specified by the number in the AS's name. Thus, each Tier 2 ISP pays transit charges to a Tier 1, while each Tier 3 ISP pays to Tier 2 ones. The letters on the names are used to assist in distinguishing the ASes belonging to the same Tier. Thus, a peer in $2A$ will receive the same g value (thus, forming one group) for peers from $3C$, $3D$, $2C$ and $2D$, since they are all two hops away from $2A$. However, exchanging traffic with $3C$ and $3D$ is cheaper than exchanging traffic with $2C$ or $2D$ for ISP $2A$, since, as shown in Figure 3.3, $2A$ and $2B$ have a peering link with each other. Preferably the peer in $2A$ could connect to as many possible peers as he can from $3C$ and $3D$ before connecting to $2C$ or $2D$. The knowledge about the customers of the peering ISP can be retrieved by the BGP announcements and thus acquisition

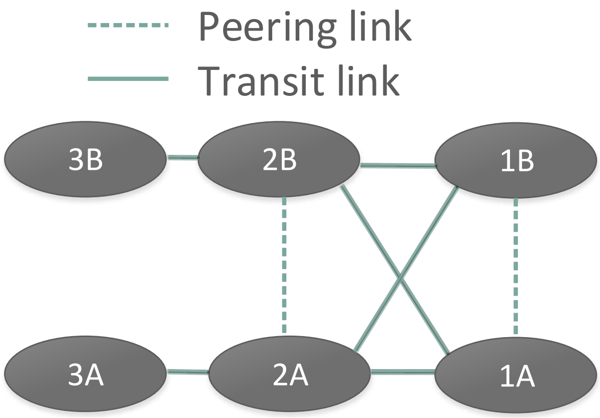

Figure 3.4: Multi-homing ISPs

of this knowledge does not require explicit collaboration. However, this is not the case for further remote ISPs. If the peering ISPs collaborate further by agreeing to split the remote ISPs into two sets and promote different sets to their peers, they can attain more benefit by reducing their inter-domain traffic and also improve or maintain the performance of the application. For example, if $2A$ and $2B$ collaborate with each other, except for the ranking higher the customer ISPs, they could also rank differently $2C$ and $2D$ ISPs. In such a way, $2A$ could prefer $2C$, while $2B$ could prefer $2D$, reducing their inter-domain traffic without providing the same resources to their end-users increasing or maintaining their performance. Thus, only when $2A$ **and** $2B$ **collaborate with each other**, they can exchange the preference values (from where this knowledge is extracted) that the overlay entity of each ISP gives to other ASes.

Along the same line, the explicit collaboration between the ISPs is also needed in case of multi-homing (see Figure 3.4). Thus, if $2A$ is multi-homed to $1A$ and $1B$ and $2B$ the same, they can collaborate to exchange preferences. $2A$ will prefer $1A$ over $1B$ and $2B$ will prefer $1B$ over $1A$. This can result in reduction in inter-domain traffic (in both links for both ISPs), without affecting the performance of the peers since they will target first, peers from different ASes.

A different collaboration is also possible with the use of the mechanisms. Tier 2 NSPs provide connectivity services to their customer NSPs. In case they collaborate with their customers, they provide them the preferences about remote ISPs, which could be their peering ISPs and the customer of those, or Tier 1 ISPs, which charge less the Tier 2 ones. This way, Tier 2 ISPs can form clusters consisting of them (the peering Tier 2 ISPs) and their customers. In those clusters they can promote locality and a common strategy about the remote ISPs. In the topology depicted in Figure 3.4, if ISP $2A$ collaborates with his customer $3A$, then he declares that he prefers first $2B$, then $3B$ and last $1A$. The rest of ISPs may be ranked by proximity (BGP hops).

Note that Tier 1 ISPs do not need that further collaboration because they do not pay transit, they all peer with each other. Also peerings of Tier 2 ISPs are not transitive in the sense that if $2A$ peers with $2B$ and $2B$ with $2C$ also, then $2B$ will not transfer traffic from $2A$ to $2C$. Thus, Tier 1 ISPs are always needed. On the other hand Tier 2 and Tier 3 ISPs need to reduce their transit inter-domain traffic.

We propose two collaborative approaches that take advantage of this knowledge, referred to as Collaborative BNS-BU and Layered Collaborative BNS-BU. We target on Win-Win (or No Lose if not a Win situation cannot be attained) situations between the ISPs and their end-users (peers). For the ISPs, the Win situation amounts to the reduction of the costs in the inter-domain links, while for the peers to the reduction on the file download times that they experience.

Note here that the ideal mechanism should encompass the full knowledge of the whole system from the overlay servers. They should know all peers in the swarm, their connection speeds, and all chunks they have at any moment. They should advise the peers to which neighbors to connect. The optimal choice would be made for each peer separately but also in such a way that the sources are balanced among the peers and there is no starvation. This will result in too much overhead for the clients and the servers due to constant messages exchanging between them for informing the server about the chunks. Also, the servers should communicate with each other. Peers cannot change their connections to other neighbors that quickly, thus they may lose a better candidate. Due to all that reasons the download performance of the peers would be highly deteriorated.

ISPs Business Targets
The basic business target of the ISPs is to reduce their costly inter-domain traffic. A secondary one is the performance that their customers are experiencing. For these reasons they collaborate already using peering agreements. We focus on enhancing this collaboration for P2P applications in order to further reduce the traffic that passes through the inter-domain links with the upper Tier transit ISP. The remote resources that produce that traffic should be balanced by others that will use the peering link or other inter-domain links not costly for the ISP. Also, at the same time it is desirable that the performance experienced by users remains unaffected or even improves. This gives the incentive to the Application providers and end-users to adopt the mechanisms in order to benefit from high quality services and/or from specific incentives given by their NSPs such as reduced prices particularly if performance related incentives are also strong.

3.3.2 Collaborative BNS-BU

Collaborative BNS-BU takes into consideration the business relationships of the ISPs in order to form the groups of peers differently from BNS-BU. The 1st-value group comprises local peers and peers from the peering AS, thus forming a larger group than in BNS-BU. The 2nd-value group consists of peers from the customer ASes of the ISPs in the first group. Larger groups are formed, for the first two groups, compared to BNS-BU in order to provide peers with more resources, thus boosting their performance. In Figure 3.5 we present the ranking that the overlay server provides to the peer in $2A$ under the BNS-BU algorithm. The locals belong to the 1st group, the peers from the peering AS $2B$ to the 2nd group while all the others are ranked according to BGP hops. The respective ranking under Collaborative BNS-BU is shown in Figure 3.6. In this case the 1st-value group for a peer in $2A$ consists of peers from $2A$ and $2B$ while the 2nd-value group is formed by peers from the customer ASes, i.e. $3A$, $3B$, $3C$, $3D$. The rest of the groups are formed using AS hops. The formation of the second group for a peer in a Tier 3 ISP is shown in Figure 3.7 for BNS-BU, in Figure 3.8 for Collaborative BNS-BU and in Figure 3.9 for Collaborative BNS-BU, when the Tier 3 ISP collaborates with its transit Tier 2 ISP too. When they do not

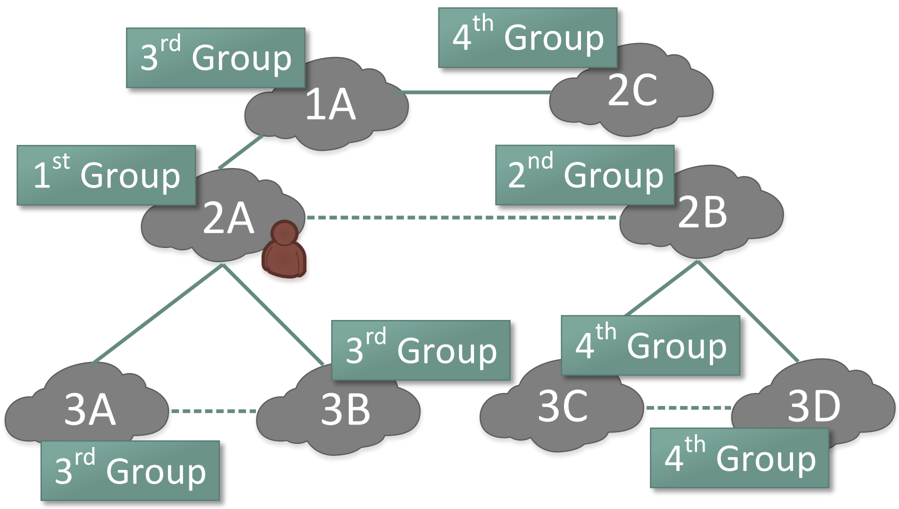

Figure 3.5: Ranking under BNS-BU

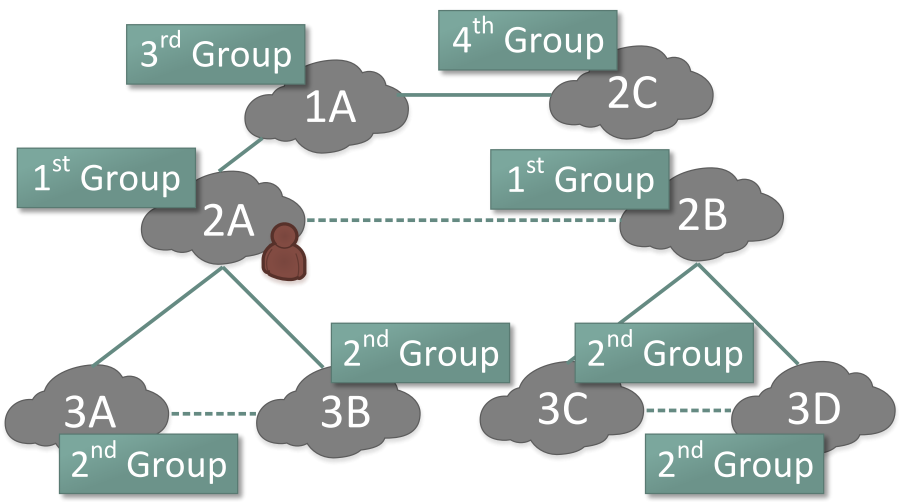

Figure 3.6: Ranking under Collaborative BNS-BU

collaborate with the upper Tier they cannot affect much the grouping since they know only their own business relationships as opposed to the Tiers above. Thus, only the highest-value group of locals and peers from peering ASes is formed and the rest stay unaffected. On the other hand, if **Tier 3 ISPs collaborate with**

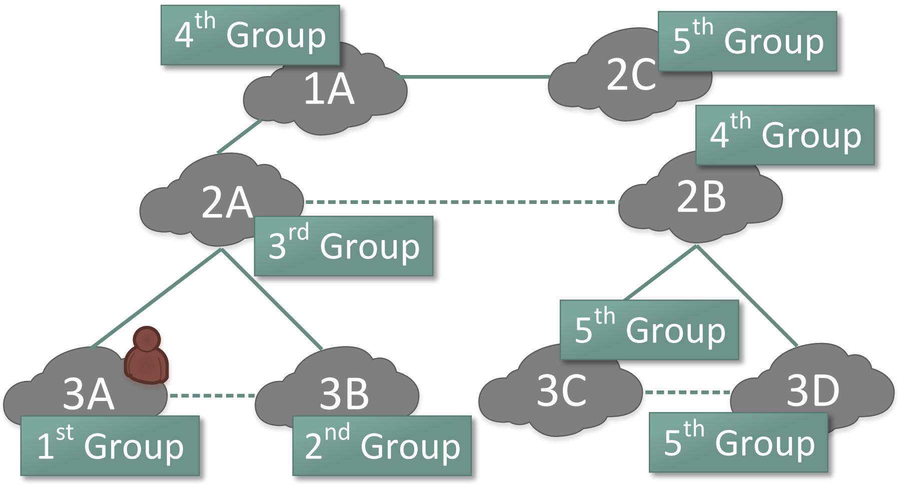

Figure 3.7: Ranking under BNS-BU (Tier 3)

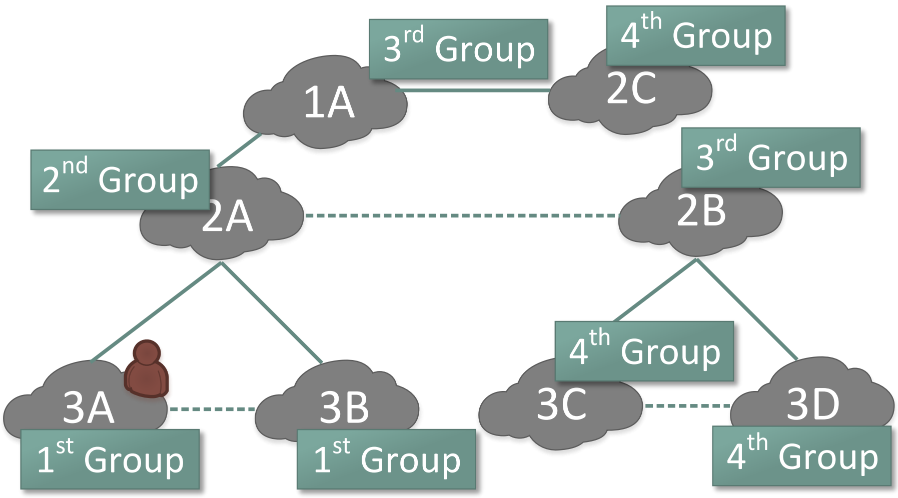

Figure 3.8: Ranking under Collaborative BNS-BU (Tier 3)

Tier 2 ones, the 2nd-value group of Tier 3 ISP $3A$ consists of peers from $2A$, $2B$, $3C$ and $3D$, as shown in Figure 3.9. Under the collaboration between Tier 3 and Tier 2 ISPs, the former may not be able to reduce their inter-domain traffic, since they do not implicate in so many relations (they do not have customers).

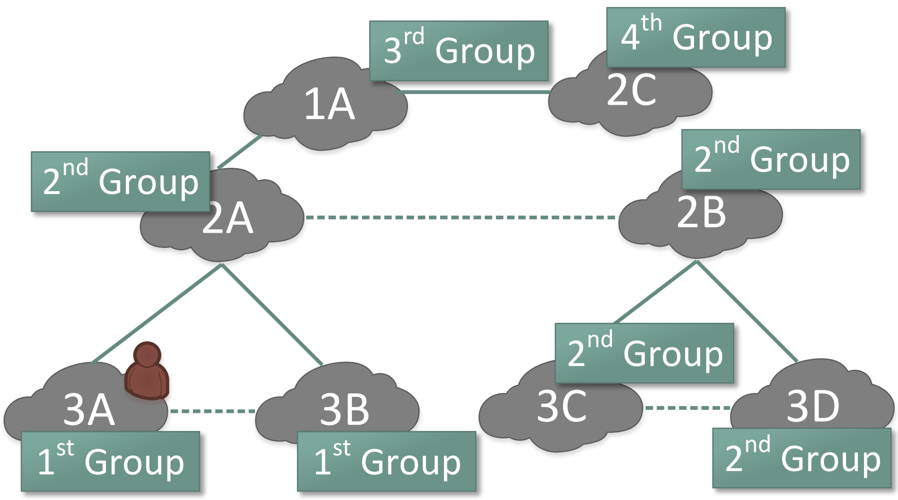

Figure 3.9: Ranking under Collaborative BNS-BU (Tier 2 and Tier 3)

On the other hand, Tier 2 ISPs may further reduce their inter-domain traffic.

3.3.3 Layered Collaborative BNS-BU

Layered Collaborative BNS-BU uses a slightly refined technique. We introduce priorities based on BGP hops in the large groups defined by Collaborative BNS-BU. This approach differs from the previous one in the number of groups. Thus, under this mechanism a peer first connects to all resources found locally before it chooses a peer from the next group, i.e. from the peering ISP, boosting this way locality. Thus, the first group, as formed in the Collaborative BNS-BU case, is split in two groups, which coinside with those of plain-BNS-BU. The 2nd-value group of the previous approach is split to multiple smaller groups according to BGP hops. Smaller groups are used in order to further promote locality and proximity once business relations are taken into account. Indeed, due to such small groups, a peer will connect to all of the peers in a "closer" group before moving to the next one. An example is shown in Figure 3.10, a peer in ISP $2A$ would receive the following group of peers: 1st group - local peers, 2nd group - peers from $2B$, 3rd group - peers from customers of $2A$ ($3A$, $3B$) and 4th group - peers from the customers of $2B$ ($3C$, $3D$). The rest of the ASes are formed into

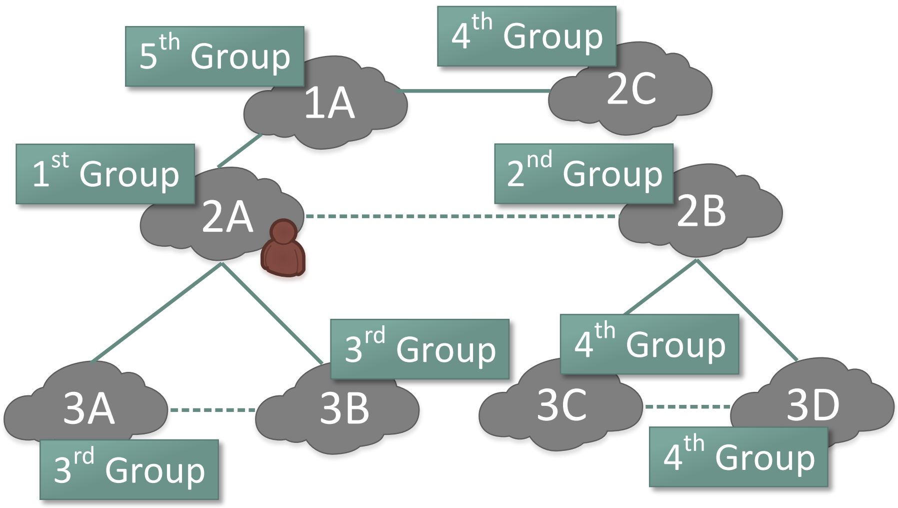

Figure 3.10: Ranking under Layered Collaborative BNS-BU

groups according to the BGP hops. This different ranking can be compared to those of the plain BNS-BU of Figure 3.5 and Collaborative BNS-BU of Figure 3.6.

It is worth noticing that for Tier 3 ISPs this approach forms groups that are identical to the plain-BNS-BU groups unless cross-Tier collaboration applies between Tier 2 and Tier 3, as mentioned in the previous section. In such a case, the ranking is done as shown in Figure 3.11.

3.4 Experimental Evaluation

3.4.1 Simulation Set-up

For the evaluation and comparison of our business-aware mechanisms with the locality-aware ones, i.e., plain BNS-BU, we chose to simulate them using a controlled environment. We created more complicated topologies than those of the examples in sub-section 3.3. We present here, in Figure 3.12, a sample topology. Each AS is identified by a unique name, which consists of a number that indicates the Tier that this ISP belongs to, and a letter that distinguishes it from others of

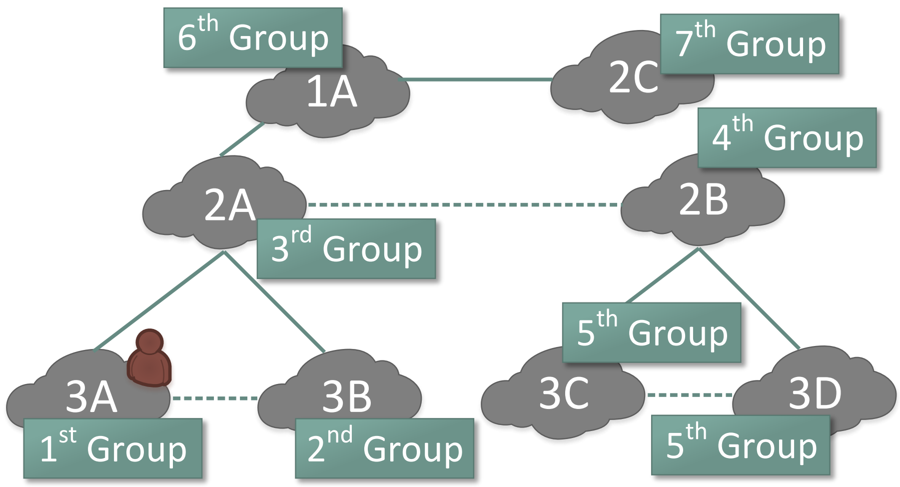

Figure 3.11: Ranking under Layered Collaborative BNS-BU (Tier 3)

the same Tier. There are eight Tier 3, three Tier 2 and one or two Tier 1 ISPs in the topology of Figure 3.12. Tier 2 ISPs have twice as many peers as Tier 3 ones, a set up that realistically reflects Internet. Tier 1 ISPs, when they have peers in the swarm, also have double peers than Tier 2 ones. Furthermore, an overlay server relies in each ISP for ranking the peers in list of a requesting peer. This server is aware of the business relationships of the ISP it belongs to and each time runs one of the various ranking approaches already presented. Moreover, this server assists peers to select which part of the content will download from each peer in the Splitting of Chunks approach that will be presented later. All topologies used are rich and representative enough to motivate our mechanisms and better exploit their potential by employing the business relations among ISPs of two different Tiers. At the same time the topologies are simple enough for the results to be easy to analyze and comprehend.

We used Protopeer simulator [36], developed in SmoothIT project [23], which has used for the evaluation of plain-BNS-BU [22]. Protopeer is a toolkit for distributed systems prototyping, which allows the fast development of overlay applications such as BitTorrent, due to its series of features. It enables the implementation of delay-bound and bandwidth-bound applications and facilitates the injection of arbitrary events like churn of peers or changes in peer behaviours.

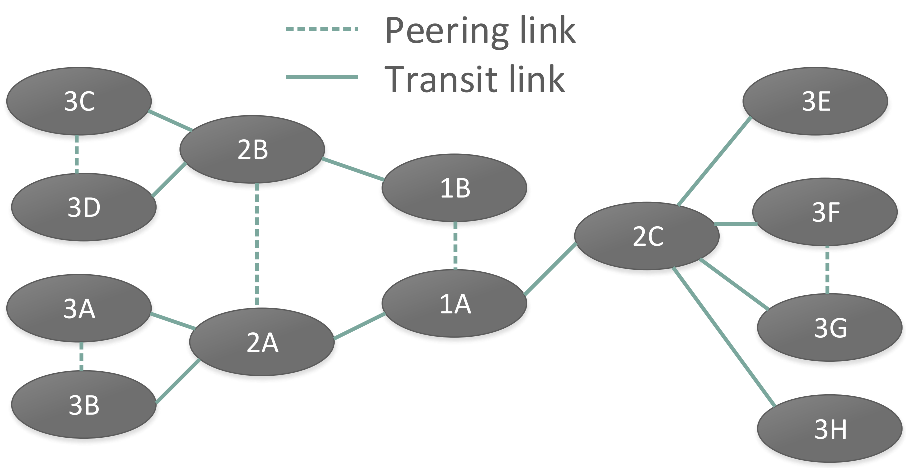

Figure 3.12: Asymmetric Simulated Topology

Protopeer simulator was developed in Java language, which makes it appropriate for the implementation of BitTorrent like mechanisms and provides tools for system-wide measurement aggregation that facilitates the manipulation of large amount of data. BNS and BU mechanisms were already implemented in the simulator. For their implementation changes where made at the client part, since the has to contact the overlay server and then run BNS and BU according to the ranked list. Thus, the peers connects to the overlay after he obtains a list from the tracker. The next change concerns BNS. The user does not connect randomly to peers from the list, but after sorting it, he tries to connect to the 90% of all connections based on the ranking. The rest 10% of connections is done randomly. For the business-aware mechanisms we altered the ranking methods of the overlay server in order to include the collaboration between the ISPs, but no changes are made in the clients. Among the provided network models we used a flow based model, which supports a simple flow control mechanism. The capacity of a link is shared among the connections currently established on a specific link. Also we used the Incremental-Max-Min-Fair-Share principle, proposed by [37] and implemented by [15], which states that the assignment of bandwidth to the connections is done in a way that the minimum bandwidth among all connections is maximized in each link. The recalculation of the bandwidth is done periodically for the of connections that are currently active in the network. We used the implementation of BitTorrent as well as of BNS-BU as provided by the authors of [16].

The peers are connected to the ASes with access speed equal to 16Mbps for download and 1Mbps for upload, roughly the typical speed values of DSL lines today. The network delay between any pair of peers is 10msec regardless their physical location. All inter-domain links have symmetrical capacities, while the access links of peers constitute the only bottlenecks in the network. All peers exchange a file whose size is 154.6MB. For simplicity reasons, we simulated one single swarm for evaluating our mechanisms. Peers arrive in the swarm following a deterministic distribution. Every 30 and 60 sec Tier 2 and Tier 3 ISPs respectively acquire one more peer. Also, after downloading the whole file, all peers seed it for 3 minutes before they exit the system. Thus, as measured during the simulations, the swarm contains about 100 to 200 peers on the average, a typical size for medium-sized swarms, as reported in [35]. Also, the simulations run for 6.5 hours. For the results we subtracted the first 1.5 hours when the system is stabilizing.

The ISPs on which we focus for the evaluation of our mechanisms are $2A$ and $3A$ and their respective peering ISPs and customers($2B$, $3B$, $3C$, $3D$). The rest of the ASes run always plain BNS-BU in order to ease our comparisons. The main metrics of interest are the mean inter-domain traffic exchanged between ISPs $2A$ and $3A$ and between ISPs $1A$ and $2A$, as well as the 95th percentile of that traffic that is used for charging. The samples for the 95th percentile are taken every moment. Furthermore, we examine the mean download times of the peers in $3A$ and $2A$. The former measurements are used to assess the savings for the ISPs, while the latter to assess the impact of the mechanism on the user performance. We calculated the mean values per minute for 10 runs of each experiment and the confidence intervals for a confidence level of 95%. The size of confidence intervals was below 6% of the corresponding mean value.

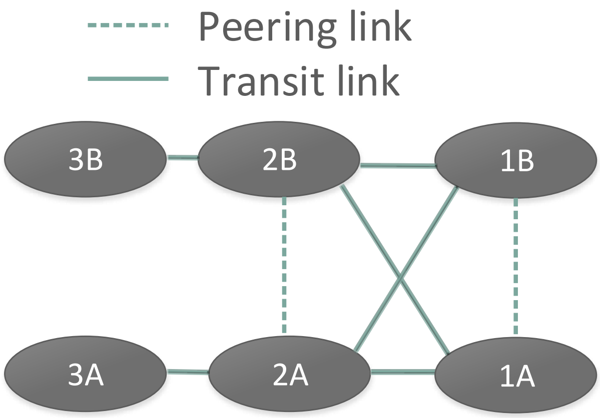

Figure 3.13: Multi-homing ISPs

3.4.2 Experimental Evaluation

3.4.2.1 Collaborative BNS-BU and Layered Collaborative BNS-BU

Collaborative BNS-BU and Layered Collaborative BNS-BU differ in the number of groups of remote peers that are created. Since Layered Collaborative BNS-BU have many small groups, we expect that the traffic may be slightly reduced on some inter-domain links since proximity is further promoted. We will evaluate both mechanisms comparing them to plain BNS-BU. First we run a simple symmetric topology, where also Tier 2 ISPs are multi-homing in order to measure the effect of the explicit collaboration for remote and at the same time multi-homing NSPs. The topology is depicted in Figure 3.13. In this topology ISP $2A$ has a peering agreement with ISP $2B$ but also is connected with Tier 1 ISPs $1A$ and $1B$, as $2B$ also does. Thus, through their collaboration they target to reduce their inter-domain traffic in both of their links that charges apply. They will, of course, increase the priority of the peers that belong in $3A$ and $3D$ since they are their customers, but also they can "prefer" a specific inter-domain link against the other. This, requires their explicit collaboration in order to agree about the preferences, not that much for reducing their inter-domain traffic but for performance reasons. In case they do not collaborate explicitly, their peers may face resource starvation. Hence, $2A$ could first prefer the local peers and the peers from the peering ISP $2B$ and then prefer those from the customer ISPs $3A$ and $3B$, but instead of having the same preference value for peers from ISPs $1A$ and $1B$, he could choose first peers from $1A$ and then from $1B$. Also, $2B$ could make the respective preferences, by ranking higher peers from $1B$ than $1A$. In order to show the effect of the collaboration between the Tier 2 ISPs $2A$ and $2B$, we run three different scenarios; in the first only ISP $2A$ adopts the mechanism and hence there is no collaboration. In particular, for ISP $2A$ is possible to run the mechanism alone, since he is aware of the customers of ISP $2B$ due to the BGP announcements under their peering agreement. In the second scenario both ISPs $2A$ and $2B$ adopt the mechanisms but without explicit exchange of any preferences about remote NSPs, while in the third scenario they do collaborate by agreeing on splitting the remote ISPs in two sets i.e., $1A$ and $1B$. We remind here that the rest of the ISPs that do not run any of our approaches, run plain BNS-BU, since as authors showed in [22] is beneficial for them in terms of inter-domain transit traffic reduction.

The results showed that in the scenario where only $2A$ runs the specific mechanism the reduction in the inter-domain traffic in all links 1A2A, 1B2A, 1A2B, 1B2B, is less than the other scenarios. The reduction in the inter-domain traffic in the link 1A2A is close to 51% comparing to plain BNS-BU scenario. The respective reduction in the link 1B2A is 55%. Due to the changes in the preferences of 2A, also 2B face a reduction (about 6% to 12%). The download time of the peers in $2A$ is increased by 9% due to the asymmetry they face in ranking. In case ISP $2B$ adopts also the mechanism but without any collaboration with ISP $2A$ then the reduction in all the inter-domain links with the upper Tier is around 57%. In case ISPs $2A$ and $2B$ explicitly collaborate with each other and exchange preferences about $1A$ and $1B$ then the reduction in all links is about 60%. The download times of the peers are slightly increased compared to BNS-BU (less than 4%, or 3 sec). Note here, that the traffic in the peering link was increased in all cases but its ratio remained closed to 1. The increase in peering traffic is a desirable effect for the peering ISPs since, as shown in Figure 3.2[1], the more Mbps pass through the link the more effective the peering for the ISPs. Of course, we assume that since they already have a peering agreement, the line "Cost of

[1]Source: Dr. Peering

Peering" is below the "Transit Price" one for the traffic prior to applying our mechanisms. Thus, explicit collaboration is needed for the peers to be treated symmetrically in ranking, but also for avoiding starvation of resources due to ranking the same peers from one AS.

We have also run a scenario where ISP $2A$ explicitly collaborates with his customer ISP $3A$. In this case, the reduction in inter-domain traffic of the link 1B2A, which is not preferred by $2A$, was as large as 65%. Also, the inter-domain traffic in the link 2A3A remained unaffected, giving the opportunity to Tier 2 ISP $2A$ to have an incentive to compensate his customer. However, due to asymmetric ranking of the peers of $2A$, again in this scenario their download times are increased by 9%, which corresponds to 3 seconds. The download times of peers in $3A$ are not affected. It is expected that if Tier 2 ISPs $2A$ and $2B$ collaborate with each other and with their customers then the reduction of the traffic in their inter-domain links will be higher. Indeed in such a case, the inter-domain traffic is reduced from 62 to 68% for the traffic of the inter-domain links of $2A$ and $2B$ with the upper Tier 1 ISPs. However, in this case the traffic in inter-domain link 2A3A is increased, because the peers in $3A$ are connected to more peers from the cluster formed of $2A$, $2B$ and $3D$. Peers in $3A$ download in 20% less time the file. Hence, peers in $3A$ stay in the swarm less time that in BNS-BU decreasing the amount of peers per minute that can be found locally. For this reason, peers in $3A$, and respectively in $3B$, try to connect to remote peers. The download times of the peers in the other ASes ($2A$ and $2B$) remain unaffected. In such a case, Tier 2 ISPs may provide the appropriate incentives to their customer ISPs in order to collaborate. Note here, that the traffic in the peering link was increased in all cases but its ratio remained closed to 1.

We also examined the effect of the number of the peers that an AS has in the swarm. We ran the same experiments but this time $3A$ and $3B$ have double the number of peers in the swarm. This did not change the quantitative results of the mechanisms (compared to the previous one) but the differences in traffic are decreased by a small percentage (5-10%) due to the increased resources that are available in $3A$ and $3B$.

We have also run the scenario where $2A$ adopts the mechanism and the one where both $2A$ and $2B$ adopt it, to a larger and more complicated topology than

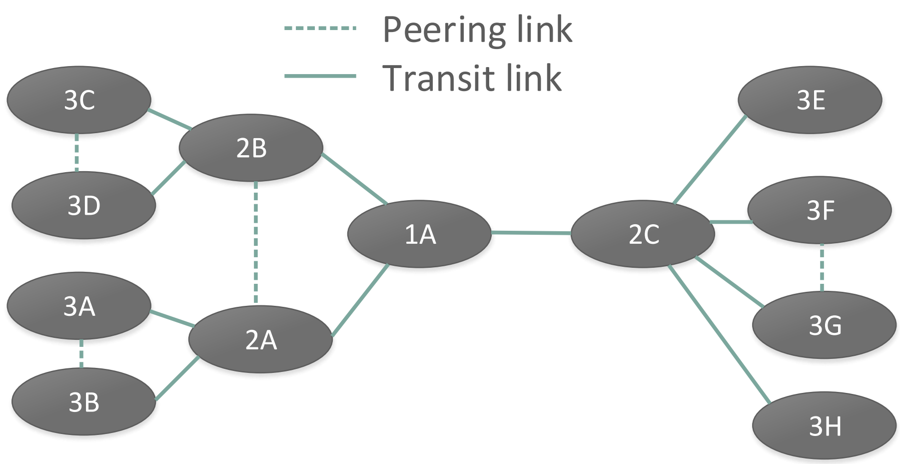

Figure 3.14: Symmetric Simulated Topology

the previous one, but this time there is no multi-homing. We examined only the incentive of an ISP to adopt the mechanism, when its peering ISP has already adopted it. Indeed, in such a topology as that of Figure 3.14, when only ISP $2A$ uses Collaborative BNS-BU, gains 27% in his total inter-domain traffic with the upper Tier ISP $1A$. However, ISP $2B$ faces an increase in his total inter-domain traffic 1A2B by 6%. Note here, that in the previous topology, in the same scenario when only $2A$ run Collaborative BNS-BU, ISP $2B$ faced a reduction in the inter-domain links. This is not the case in this topology because the remote resources are more. The traffic in their peering link is increased by 25%, while the ratio still remains close to 1.

In case $2A$ and $2B$ collaborate with each other, meaning $2B$ also runs Collaborative BNS-BU, $2A$'s total inter-domain traffic is reduced by 36%, while $2B$'s by 46%. Their peering traffic is increased, as we expected, but the ratio is close to 1. When, they collaborate with each other and thus both of them run Collaborative BNS-BU, then the reduction of the 95th percentile for $2A$ only incurs a small decrease (49% compared to plain BNS-BU), but $2B$ gains 61% more compared to plain BNS-BU.

Since those two scenarios show the effect of the further collaboration between two peering ISPs, we used also an asymmetric topology from Tier 2 ISPs perspective, for evaluating the mechanism. In this topology, we examine also the scenario where only Tier 3 ISPs that have a peering agreement with each other, such as $3A$ and $3B$, adopt the mechanism.

In Table 3.1 we present the effect of the Collaborative BNS-BU approach to the transit inter-domain traffic (in MB/s) of $1A2A$ and $2A3A$ links, as well as to the download times (in min) that peers in ISPs $2A$ and $3A$ experience. Each column of the table corresponds to a different scenario; plain BNS-BU and Collaborative BNS-BU. Collaborative BNS-BU is separated in multiple columns, each one corresponding to groups of simulations; for each group a different pair of ISPs runs the specific scenario. For each scenario the rest of the ISPs run BNS-BU since it is in the interest of ISPs to run those two algorithms, as authors in [22] showed. In particular, Collaborative BNS-BU Tier 2 means that ISPs $2A$ and $2B$ use the Collaborative BNS-BU approach while all other ISPs run BNS-BU. Collaborative BNS-BU Tier 3 means that Tier 3 ISPs $3A$ and $3B$ only use the specific approach. Tier 2 and Tier 3 refers to the case where $2A$ and $2B$ collaborate with **their customers** and all follow the specific approach. Each row comprises the mean values of a specific metric, i.e. the mean rate of inter-domain traffic $1A2A$, the mean rate of inter-domain traffic $2A3A$, and the mean download times in $2A$ and in $3A$. As shown in Table 3.1, when only ISPs $2A$ and $2B$ run

Table 3.1: Collaborative BNS-BU Approach

Metric Scenario	BNS- BU	Collaborative BNS-BU Tier2	 Tier3	 Tier2 and 3
Traffic 1A-2A (MB/s)	1.09	0.8	1.01	0.61
Traffic 2A-3A (MB/s)	11.11	11.29	11.03	11.54
DT 2A (min)	2.92	2.99	2.98	2.03
DT 3A (min)	8.95	8.85	9.01	9.11

Collaborative BNS-BU (Collaborative BNS-BU Tier 2), $2A$ manages to reduce its transit inter-domain traffic by 26% (from 1.09 to 0.8) essentially without affecting peers' performance, thus attaining a Win-No Lose situation. Traffic between $2A$ and $3A$ and download times for peers in 3A are only marginally increased (1.6% and 1.1% respectively). Thus, for Collaborative BNS-BU Tier 2 there is a Win-No lose situation for ISPs in both Tiers (for both ISPs $2A$ and $3A$). In case where ISPs $3A$ and $3B$, the transit inter-domain traffic is not significantly affected

(Collaborative BNS-BU Tier 3); at the same time this has a minor negative effect on peers' performance in the ISPs of both Tiers and a slight positive effect on the inter-domain traffic of 1A2A.

If ISPs $3A$ and $3B$ run Collaborative BNS-BU and $3C$ and $3D$ do so too, then Tier 2 ISPs $2A$ and $2B$ have a clear incentive to also run Collaborative BNS-BU. Indeed, this extra collaboration between them will improve the transit inter-domain traffic 1A2A by 44% and considerably improve the download times of peers in $2A$ (30.5%), (see column Collaborative BNS-BU Tier 2&3 in Table 3.1). Since in this case Tier 3 ISPs are indifferent in adopting the approach, ISP $2A$ can incite it to its customer ISPs $3A$ and $3B$ by sharing part of its own benefits with them. Similar results are obtained from the implementation of the Layered Collaborative BNS-BU for Tier 2 ISPs and for Tier 2 & 3 ISPs, due to the large amount of resources from the local and the peering ISPs.

The evaluation of Layered Collaborative BNS-BU mechanism showed similar results with the Collaborative one. This is because the promotion of proximity to distinguish local peers from those from the peering ISP does not make any significant difference, since the peers in both cases (with or without layering) connect to as much possible peers from both ISPs (local and peering). The difference is mostly seen in Tier 3 ISPs, where proximity assist in the reduction of inter-domain traffic and slightly at the performance of the peers, as shown in 3.2.

Table 3.2: Layered Collaborative BNS-BU Approach

Metric Scenario	BNS-BU	Layered Collaborative Tier2	Layered Collaborative Tier2 and Tier3
Traffic 1A-2B (MB/s)	1.09	0.8	0.63
Traffic 2A-3B (MB/s)	11.11	11.02	10.86
DT 2A (min)	2.92	3.06	3.03
DT 3A (min)	8.95	8.96	9.06

Thus, we conclude that especially large ISPs, such as Tier 2 ones, gain from deploying Collaborative algorithms for BNS-BU approaches due to fact that they can form large clusters with their peering ISPs and their customers and hence their peers can find larger amounts of resources in this cluster. The explicit agreement on collaboration between an ISP and a peering ISP, as well an ISP and its customers, is necessary in order to exchange preferences about external (from the cluster) resources. Also, the cross Tier collaboration allows the creation of the cluster since the Tier 2 ISPs exchange their preferences with their customers. When peering ISPs further collaborate with each other, inter-domain traffic exchanged through their transit links is reduced. The involvement of their customer ISPs and the creation of clusters may assist in the reduction of the transit inter-domain traffic of Tier 2 ISPs, but their links with the customers are affected, meaning that specific incentives must be given to them in order to collaborate. However, the gains on traffic highly depend on the topology and the cluster formation.

3.5 Splitting of Chunks

3.5.1 Theoretical Approach

To further exploit the initial collaboration of the ISPs, i.e., their peering agreements, we developed another mechanism that provides them with the opportunity to further collaborate in order to reduce the redundancy in the downloading content from non-local peers (or ISPs). The proposed mechanism suggests that the peering ISPs can share costs by deciding that their peers split the content and download different parts of content through their transit links and then exchange the rest of the parts of it via their peering link. Indeed, since the peers in each peering ISP will all download a subset of chunks using the transit link, the ISP will be charged less by his transit ISP of the upper Tier. Note here that no restrictions apply on the local peers.

Peering ISPs first decide which chunks of the content will be downloaded by each one's peers from remote ASes. To illustrate our approach, we introduce the following rule for splitting: the chunks are partitioned in two subsets of equal size according to their ids, e.g. in even and odds or first half and second half or any other similar way. The rest of the chunks that the peers will not download from the remote ASes will be retrieved from the peering link or from local peers. As in the plain BNS-BU, the peer may identify its neighbours by the ranked list of peers that he retrieves from the overlay server.

Splitting of Chunks can be implemented on top of BitTorrent but since the peering ISPs have to collaborate explicitly the deployment of the overlay servers introduced for the BNS-BU mechanisms by SmoothIT project ([23]) is necessary. The servers should notify each peer which part of the content are allowed to download from each specific peer in their list. The client side should be modified in order to connect to the server and send the lists obtained from the tracker. Also, the client must be modified in order to request the appropriate chunks from each of his neighbors. However, since according to the authors in [22], the BNS-BU mechanisms should be used together and they are beneficial for the ISPs, we consider in our work that the ISPs already implement them. Hence, the modifications that have to be made in order for the Splitting Chunks to be implemented are less. In particular, the ranked list needs to contain another field, which indicates the type of the chunks (or in other words the set of ids) that the peer should download from every peer in the list. Since modifications have to made in the client, the appropriate incentives have to be provided to application providers and/or end-users in order to adopt the specific client. In our evaluation we split the chunks according to even and odd ids. In this case the list contains triplets of {address - group's value - chunkTypeID}, (a, g, c). Thus, the querying peer uses g to identify proximity of a peer for BNS and BU algorithms and c to identify which chunks he can download from this particular peer. Let us suppose that ISPs $3A$ and $3B$, as shown in Figure 3.15, are collaborating using the proposed mechanism and have decided that peers from $3A$ will download the even chunks of the content (c=2) while peers from $3B$ the odd ones (c=1). Then, a peer from $3A$ receives three kinds of triplets, one for a peer from $3A$, ($a1$, $g1$, $c1$), one for a peer from $3B$ ($a2$, $g2$, $c2$) and one for a peer from $2A$ ($a3$, $g3$, $c3$). The first peer, $a1$, belongs to $3A$, thus $g1$=1 and $c1$=0, which indicates that peer $a1$ is local and the requesting peer can download every chunk from there. For the second peer $a2$ (in $3B$) $g2$=2 and $c2$=0, which indicates that peer $a2$ belongs to a peering ISP and the peer can download every chunk too. Finally, for the third peer (in $2A$) $g3$=3 and $c3$=2, which indicates that peer $a3$ belongs to an ISP one transit hop away and the peer can download only even chunks from there. The respective field $c3$ received by a peer in $3B$ (from the server in $3B$) would be equal to 1 and he could only download odd chunks. $c1$ and $c2$

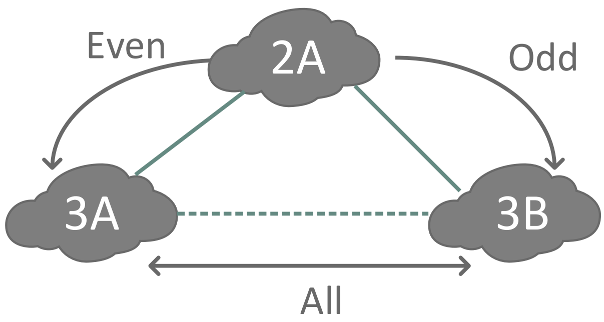

Figure 3.15: Splitting of Chunks

for that peer in $3B$ would be the same. Also in order for a peer to download content in accordance to Splitting of Chunks, two extra modifications have to be introduced. In particular, the peer once acquiring the message with the list of the available chunks of a neighbour, has to decide if he is interested in any of the chunks this neighbour has (and eventually download them), as normally happens in BitTorrent mechanism. Therefore, the peer needs to check whether the neighbour possesses any of its missing chunks and also if those chunks belong to the subset of chunks that the field c indicates for that neighbour. If this indeed applies, then the peer declares its interest to that neighbour and requests the permissible chunks.

3.5.2 Experimental Evaluation

In this section, we present the experimental performance assessment of Splitting of Chunks mechanism and its comparison to BNS-BU mechanism and our collaborative mechanisms. As explained before, according to the authors in [22], the combination of BNS and BU mechanisms is beneficial for the providers and this is why we consider them as already adopted. In the first set of simulations, we run Splitting of Chunks on top of BNS-BU mechanism in order to evaluate our approach. The topology used is the asymmetric one depicted in Figure 3.12. Contrary to the previous mechanisms, the topology used does not affect the performance of Splitting Chunks in terms of traffic changes. The download times of the peers are affected based on the number of local and peering peers in the swarm, since the peers are allowed to download all chunks from these ones.

The columns of Table 3.3 present the different scenarios; plain BNS-BU and Splitting of Chunks combined with plain BNS-BU. BNS-BU runs in all ISPs of our topology while there are different set of experiments for Splitting of Chunks. We mentioned before that Splitting of Chunks need an explicit agreement on collaboration in order for the ISPs to download different part of the content from the inter-domain links. However, an ISP could possibly run the mechanism alone by downloading half the content from his transit NSP. But in case that both want to run the mechanism they have to collaborate in order to avoid content starvation of their peers. Thus, in order to evaluate how important the collaboration is for running this mechanism we first run a scenario where only ISP $3A$ adopts the mechanism (SC 3A). We decided to run this scenario because from Tier 3 ISPs the topology is symmetric in the sense that both $3A$ and $3B$ are connected to the same Tier 2 ISP. Then we run the collaborative scenario (SC Tier 3) where both Tier 3 ISPs $3A$ and $3B$ adopt it. In this case $3A$ and $3B$ run Splitting of Chunks by agreeing on which part of the content will download from remote ISPs. Then we introduce the mechanism to Tier 2 ISPs $2A$ and $2B$, who collaborate with each other (SC Tier 2). In the last scenario SC Tier 2 & Tier 3, $2A$, $2B$, $3A$, $3B$, $3C$ and $3D$ employ it on pairwise basis. The rows of Table 3.3 comprise the mean traffic volume for inter-domain links 1A2A and 2A3A and the mean download times for peers that belong to ISPs $2A$ and $3A$.

Table 3.3: Splitting of Chunks on top of plain BNS-BU

Metric - Scenario	BNS-BU	SC Tier 2	SC 3A	SC Tier 3	SC Tier 2 & Tier 3
Traffic 1A-2A (MB/s)	1.09	0.92	1.5	2.2	0.78
Traffic 2A-3A (MB/s)	11.11	10.99	7.43	7.84	11.11
DT 2A (min)	2.92	3.04	2.95	3.00	2.96
DT 3A (min)	8.95	9.25	11.64	11.19	8.98

In the first scenario where only $3A$ adopts the mechanism, the inter-domain traffic in the link 2A3A is reduced by 33% and the download times of the end-users suffer a deterioration of 30%, compared to the plain BNS-BU. At the same time $3B$'s inter-domain traffic with $2A$ is increased by 10%. This gives him an incentive to collaborate with his peering ISP $3A$. If they indeed collaborate (SC Tier 3 scenario), both ISPs $3A$ and $3A$ manage to reduce their inter-domain traffic exchanged with their transit ISP ($2A$) by 29%, compared to the plain BNS-BU. The download times for their peers deteriorate less, but still by 24%. Since the performance of their users is strongly deteriorated it is highly unlikely for them to proceed with such an approach. Note here that in case they adopt this mechanism, the traffic of the transit inter-domain links of the Tier 2 ISP $2A$ are highly deteriorated (by 40%), since his peers cannot find the resources needed from the customer ISPs.

In the scenario where Tier 2 ISPs $2A$ and $2B$ collaborate with each other, the inter-domain traffic 1A2A is reduced by 15.6%, while the traffic in link 1B2B is reduced by 23%. The difference between the percentages is caused due to the asymmetry topology used. Also, the performance of their end-users remain unaffected.

However, when Tier 2 ISPs proceed in adopting Splitting of Chunks, Tier 3 under the right incentives may adopt the approach since there is no effect on their inter-domain traffic nor the download times of their users. Moreover, in such a case, Tier 2 ISPs attain a reduction of 30% in their inter-domain traffic, comparing to plain BNS-BU.

Since the introduction of Splitting of Chunks in Tier 2 ISPs is applicable and promising, we continue our experimental analysis by introducing also Collaborative BNS-BU and Layered Collaborative BNS-BU in Tier 2 ISPs and combining these approaches with Splitting of Chunks. In Table 3.4 we present the previous results for BNS-BU, Collaborative BNS-BU, Layered Collaborative BNS-BU and the Splitting of Chunks approach on top of those algorithms. The first column of the table comprises the results of the BNS-BU scenario. The second and the third column refer to two scenarios based on Collaborative BNS-BU in Tier 2 ISPs $2A$ and $2B$ (second column), which coincides with the relevant results in Table 3.1 and Splitting of Chunks on top of Collaborative BNS-BU in Tier 2 ISPs $2A$ and $2B$ (third column). The last two columns Collaborative BNS-BU is replaced with Layered Collaborative BNS-BU. The rest of the ISPs run BNS-BU. The effect of Splitting of Chunks on top of Collaborative BNS-BU, either with or

Table 3.4: Splitting of Chunks on top of Collaborative approaches in Tier 2

Metric Scenario	BNS- BU	Collaboration BNS-BU Tier 2	 SC Tier 2	Layered Collaboration BNS-BU Tier 2	 SC Tier 2
Traffic 1A-2B (MB/s)	1.09	0.8	0.73	0.8	0.74
Traffic 2A-3B (MB/s)	11.11	11.29	11.16	11.02	11.26
DT 2A (min)	2.92	2.99	2.97	3.06	3.03
DT 3A (min)	8.95	8.85	8.88	8.88	9.06

without layers, is almost the same. The new approach results in an inter-domain traffic reduction about 9% compared to Collaborative BNS-BU and 33% compared to BNS-BU, without essentially affecting users' performance in both Tiers. Thus, Tier 2 ISPs that have a peering agreement can adopt Splitting of Chunks on top of **any BNS-BU approach** that they follow.

Since Tier 2 ISPs can be expected to implement Splitting of Chunks on top of Collaborative BNS-BU approaches adopted only by them, we also have to investigate the textbfreaction of Tier 3 ISPs. Tables 3.5 and 3.6 comprise the results of two groups of experiments namely the set with Collaborative BNS-BU and the set with Layered Collaborative BNS-BU respectively. The first column of each group comprises the corresponding version of BNS-BU that $2A$, $2B$ and their customers run. The second, third and fourth columns refer to Splitting of Chunks approach. In the second one only Tier 2 ISPs $2A$ and $2B$ adopt the mechanism while in the third only Tier 3 ISPs $3A$ and $3B$ adopt it. In the fourth column we depict the result of the scenario where Tier 2 ISPs $2A$, $2B$ collaborate with each other and also with their customers $3A$, $3B$ $3C$ and $3D$ run the respective collaborative BNS-BU. Also the rest of the ISPs run BNS-BU.

When only Tier 2 ISPs $2A$, $2B$ run Splitting of Chunks on top of Collaborative BNS-BU, they attain a reduction of their transit inter-domain traffic by 30% (60% compared to plain BNS-BU) essentially without affecting peers' performance, thus attaining a Win-No Lose situation. Traffic between $2A$ and $3A$ and download times for peers in $3A$ are marginally affected (3% increase and 3.9% improvement respectively). Thus, there is essentially a Win-No lose situation for ISPs in both Tiers.

Tier 3 ISPs will not adopt Splitting of Chunks as in the previous scenarios, due

Table 3.5: Splitting of Chunks on top of Collaborative BNS-BU

Metric Scenario	Collaboration			
	BU-BU	Splitting of Chunks		
	Tier 2 & 3	Tier 2	Tier 3	Tier 2& 3
Traffic 1a2a (MB/s)	0.61	0.43	0.8	0.4
Traffic 2a3a (MB/s)	11.54	11.9	8.17	11.8
DT 2a (min)	3.02	2.99	2.95	2.98
DT 3a (min)	9.11	8.75	11.1	8.89

Table 3.6: Splitting of Chunks combined on top of Layered Collaborative BNS-BU

Metric Scenario	Layered Collaboration			
	BNS-BU	Splitting of Chunks		
	Tier 2 & 3	Tier 2	Tier 3	Tier 2 &3
Traffic 1a2a (MB/s)	0.63	0.61	0.89	0.81
Traffic 2a3a (MB/s)	10.86	11.05	7.69	11.15
DT 2a (min)	3.03	3	2.94	2.93
DT 3a (min)	9.06	9.06	11.31	8.82

to higher download times of their users. In case that Tier 2 ISPs already deploy Splitting of Chunks on top of Collaborative BNS-BU, Tier 3 ISPs are indifferent in adopting the approach. However, in the case where all adopt Splitting of Chunks we observe the lowest value of inter-domain traffic 1A2A (34% compared to Collaborative BNS-BU and , 63% compared to plain BNS-BU). Again Win-No Lose situations arise between Tier 2 ISPs and their end-users and also between Tier 2 ISPs and their customers ISPs. Therefore, ISP $2A$ may ask its customers to follow this approach sharing the benefits with them. The same observations are applicable to the case of Layered Collaboration BNS-BU.

We also run experiments where the two large peering ISPs and their customers, have a different number of peers in the swarm. We have reached the same conclusions as before, though the download times of the peers were deteriorated slightly more since the lack of resources in the peering ISP with the less peers in the swarm.

Thus, we conclude that even in case of a different approach, such as Splitting of Chunks, where the ISPs collaborate to split the content downloaded from remote ISPs, large ISPs gain from deploying it due to fact that their peers can find larger amounts of resources locally or from the customer ISPs and thus inter-domain traffic exchanged through costly transit links can be reduced. Again, it is in th interest of two large peering ISPs to form clusters with which they will promote collaboration between them and their customer ISPs in order to reduce their costly inter-domain traffic.

3.6 Conclusions

In this chapter, we introduced and evaluated collaborative variations of the BNS-BU (Biased Neighbor Selection - Biased Unchoking) locality promotion approach, namely Collaborative and Layered Collaborative BNS-BU, as well as the Splitting of Chunks approach. All of the proposed mechanisms exploit the business relationships between ISPs of either the same or different Tiers in order to attain a reduction of the costly transit inter-domain traffic. By means of simulations, we showed that large ISPs (Tier 2 in our simulations) can attain this goal, while in general not lead to a deterioration of the performance of their users. In particular, they can adopt the Collaborative BNS-BU mechanism without explicit collaboration with each other, but under a specific agreement between them they can achieve higher results. Also, when Tier 2 ISPs collaborate with each other and with their customers as well forming a cluster within which the locality is promoted, they gain the maximum benefits. However, Tier 2 ISPs have to give the right incentives to their customers in order for them to collaborate, especially when they cannot find many resources locally and thus their inter-domain traffic with the Tier 2 ISP may increase.

The introduction of Splitting of Chunks on top of the aforementioned mechanisms leads to additional reduction of the transit inter-domain traffic of Tier 2 ISPs, but just maintains user performance, thus leading to a Win-No lose situation. In general, we conclude that large ISPs have the incentives to collaborate with each other, creating large clusters within which they promote locality without affecting the performance of their users, while they can further benefit if they provide their customers ISPs with the incentive to collaborate with them.

Chapter 4

Collaboration For SLA Bundling Over Inter-domain Links

4.1 Motivation of Coordination Models

The largest portion of Internet traffic is generated by Real-Time applications, such as Netflix, YouTube etc. Also, Cloud computing becomes increasingly popular nowadays, since it provides to end-users (individuals/companies) information technology services of the desired characteristics with reduced maintenance or downtime or hardware upgrading costs. Real-time applications and Cloud Computing will provide the overwhelming majority of the service for the typical user in the near future (see also 1.1). Although, NSPs (or ISPs) are able to serve with a good QoS their customers, and they claim that there is enough capacity for such applications, this may not always be the case. The usage of smartphones, tablets and all other mobile devices is increasing at high paces. More and more applications that require high throughput and small delays, such as videos or on-line games will be provided through those devices. In case the applications also use mobile networks, where the spectrum is shared among many end-users, then there is a high risk of provision of the service with low QoS to the end-users. Thus, the collaboration between different providers, i.e, Network Service Providers (Fixed and Mobile), Cloud Providers (Infrastructure (IaaS), Platform (PaaS) and Software (SaaS)), Real-Time Application Providers, CDNs, etc., to provide high quality services to their customers becomes a necessity.

All the aforementioned providers already collaborate with each other. This is done by bilateral coordination and allows the provision of connectivity services that attain the overall connectivity of the Internet. To guarantee a customized level of performance and availability of the offered services the providers employ resource reservation control mechanisms [6]. Thus, QoS provides the level of assurance to guarantee the resource requirements of a service, according to the end-user's needs, while the associated SLAs provide the means of agreement among the involved participants upon the required level of QoS ([7]). These SLAs differ from the static and long term bilateral transit and peering SLA interconnection agreements between providers, because the QoS-enabled services are provided on top of the basic interconnection services for traffic exchange, they can have shorter time scales and are charged at extra prices.

Although the bilateral coordination between two providers in order to agree in an SLA for the provision of a specific QoS level by one to the other's customers appears to be quite simple, since they already collaborate, the coordination between three or more providers is not obvious. Many cloud providers, CDNs etc., bring their infrastructure as closer to end-users as possible in order to minimize delays, costs etc. But this does not mean that the providers will be only one hop away from the customer (counting the customer's provider). But also this is the case of the most of the paths in the Internet as indicated in [38]. Dimitropoulos et al. argue that the most common paths are comprised by three different providers between an end-user and a destination, or in other words two hops away, counting a transit provider and the customer's provider.

The provision of a guaranteed level of performance by three or more providers needs end-to-end QoS assurance. Since, as mentioned above, this is given by the use of SLAs, then the coordination among all providers in a chain is needed for the formation of end-to-end SLAs or in other words **bundled SLAs**. This bundled SLA is constructed between two or more providers and is offered to the one offering access to the end-user (more in the next Section). For the coordination between the providers of a chain for the construction of a bundled SLA, as well as, the coordination between them and the buyer provider, who purchases this SLA, the use of coordination schemes is necessary. Those schemes should comprise all the financial and information-sharing interactions among providers that enable their interconnection for the provision of the bundled SLA required, while at the same time, they must be easily deployable on top of the current Internet and cloud architecture. Therefore, deployment of a successful coordination scheme is critical for the provision of QoS-enabled inter-domain services.

In this chapter, we propose a variety of inter-domain coordination schemes and we address the information issues that may arise due to their use. The knowledge of how the distribution of information affects the formation of the end-to-end paths is necessary for the right definition of pricing and revenue sharing schemes. Also, we verify our analysis of the information issues by the assessment of two realistic and practically applicable distributed coordination schemes for interconnected providers offering QoS-enabled end-to-end cloud and connectivity services through Internet. For the assessment of the distributed coordination schemes, we derive rigorously and evaluate numerically the pricing strategies of the providers (NSPs and InfPs) participating in a chain to provide a QoS-enabled service between a source and a destination. Each provider is taken as a self-interested entity aiming to maximize its own profits, which of course depend on the other providers' actions. Thus, we formulate the relevant game-theoretic models and carry out equilibrium analysis. Based on the assessment of these models, we also offer guidelines for the choice of the right coordination scheme in practical cases of cloud and connectivity services markets, depending on the maturity of the respective market and on properties of the demand.

4.2 Introduction in Coordination Models

In Figure 4.1 we present a small topology with three "nodes" (each corresponding to a provider) that already collaborate with each other for the provision of the basic connectivity service. The nodes may represent NSPs, Cloud Providers, CDNs etc. Thus, we assume an SaaS Provider (SaaS), e.g., an online game provider, which is willing to offer his services to a customer (end-user) residing in an access provider two hops away. This access provider can also be a mobile provider, thus the end user is playing the game on his tablet or smartphone using a mobile broadband connection. Both the SaaS and the access providers have an

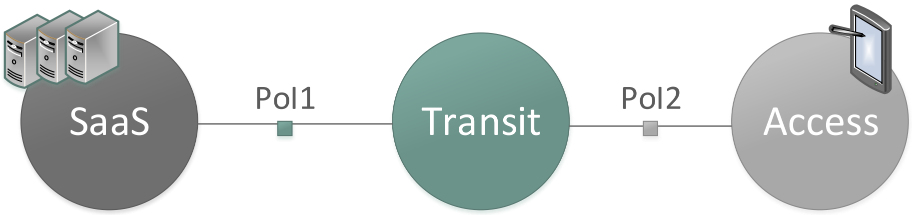

Figure 4.1: Tolopogy example

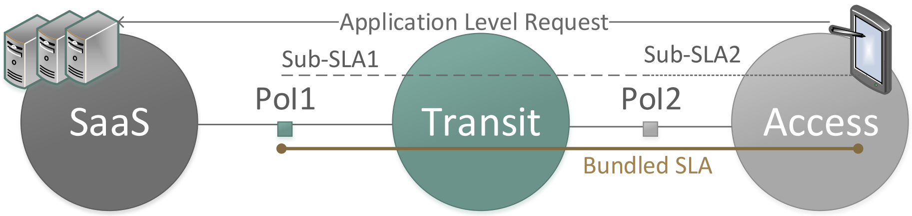

Figure 4.2: Bundling SLAs between a Cloud Provider (left) and an end-user (right).

SLA agreement (each one his own) for Internet connectivity with the same transit provider, thus forming a chain. The Points of Interconnection (PoI) describe where and how the traffic is exchanged between two providers and also indicate where the control of the traffic is passed to the next provider in the chain. The provision of the on-line game application demands specific QoS characteristics, such as small delay and a certain capacity. These characteristics may be difficult to achieve e.g., by the access provider, during the whole game period. Thus, what is needed is an assurance by the transit and the access providers to the SaaS that they are able to deliver his service under the certain QoS level. This is possible with the use of a bundled SLA.

SLA Bundling We present this example in detail way in Figure 4.2. The end user makes an application-level request to the SaaS. The SaaS in his turn requests a bundled SLA that is valid from PoI1 until the end user and specifies the QoS level. SaaS is the so called buyer of the service and the source of the traffic. The transit and access providers coordinate with each other and form the bundled

SLA combining sub-SLA1 and sub-SLA2. Sub-SLA1 controls traffic from PoI1 to PoI2 providing a certain QoS level for the traffic crossing the transit network, while sub-SLA2 provides the same level for traffic crossing access network until the destination (end user). This bundled SLA determines:

- The destination range
- A PoI until which the buyer has control of the traffic
- Specific requirements, such as maximum delay, minimum bandwidth, jitter, period of validity etc.

These parameters along with a price specify completely a service that is provided to the buyer (or in our case the SaaS), or in other words the bundled SLA that has to be created from sub-SLAs offered by the various providers in the path.

This general example of SLA composition that we just described, includes in fact two different phases; the Publishing phase and the Service Composition phase [13]. During the Publishing phase, information is released from the participants for the acquisition of some knowledge about QoS characteristics or availability of other providers. The Service Composition phase is triggered when the provider create specific SLA offers and bundle them. In the next section, we study the scenarios applicable for each of those two phases and the effect of the available information on the pricing strategies of the participants.

Information sets. During the two phases, information is announced to potential participants. This information should include the topology or else the potential participants in such a service. This is necessary in order for any NSP to find all others that may want to collaborate with him for the provision of a service that need SLA bundling. Also, when announcing a participation, NSPs should inform others about their destinations that they can serve. Other optional information concerns the QoS levels that the NSP may offer or the price. When the price is not available or when the announcements contain information that may change, we call them **Network Capabilities**. On the other hand, when the announcements contain specific information and price and they are ready to be sold, or in other words they promise to offer what they contain, they are called **SLA offers**. For the rest of our analysis we assume that these SLA offers contain:

- The logical point(s) of interconnection (PoI)
- The destination(s) network(s) prefix
- The QoS characteristics
- The expiration time of the offer and a price.

Note here that SLA offers are ready to be purchased by a buyer. After their expiration time, they are not valid. The exact information that will be available to all depends on the privacy issues that may apply. For example, there may be open markets or in the exact opposite side, federations, where strict rules for privacy may apply.

4.3 Classification and Description of Coordination Models

The assured QoS level, which is the minimum level of QoS that a service needs in order to be provided (see Chapter 2), is given as an add-on service on top of the basic connectivity one and may involve two or more providers (NSPs, Access, Mobile, Cloud etc.,). Those providers in order to construct a model service, have to coordinate with each other for exchanging information and SLA offers. Providers coordinate with each other according to coordination schemes. In order to present these schemes in a more general way, we introduce the topology depicted in Figure 4.3, which is a more abstract version of that of Figure 4.1. Also for a clearer description of the work, we will refer to all the nodes as NSPs, without losing the general context. Thus, the first NSP is the source (S) of the traffic, the last plays the role of the destination (D) of the traffic and the middle one the transit NSP (A).

We introduce two orthogonal dimensions for the classification of the coordination schemes. The combination of these categories may result in different coordination schemes. Also, as mentioned before, in each coordination scheme the NSPs participate in two subsequent phases referred in section 4.2, namely the Publishing and the Service Composition Phases. During the Publishing Phase,

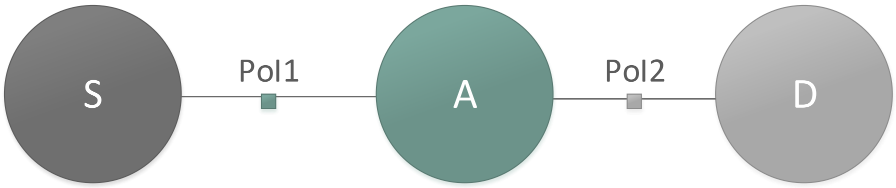

Figure 4.3: Basic Topology for the Coordination Models' Definition

the NSPs make some information available usually through Network Capabilities, while during the Service Composition one, the NSPs coordinate for the formation of the bundled SLA using SLA offers. Both of these phases highly depend on the actual coordination scheme and thus we will examine them separately for each different case.

4.3.1 Phases

As mentioned before, there are two Phases that the entities wishing to provide a bundled service have to follow; the Publishing and the Service Composition Phases. During the Publishing Phase the participants publish information about the capabilities of their networks (Network Capabilities) or in other words about the different level of QoS that they are able to provide and to which destinations for each level. These pieces of information may be published to all participants or a subset of them. Later, we discuss about how the availability of information affects each scheme.

The Service Composition Phase is triggered by the buyer or by any other node depending on the coordination scheme. This Phase is triggered when the SLA offers are announced and it is completed when an SLA is purchased. Also, for this transaction to be fulfilled, two actions have to take place: the buyer's (S) request and the bundling of the SLA-offers (i.e. SLAs including price) of the participants in a chain. The bundling of the sub-SLAs may be done by a central entity or by the providers or even by the buyer. We will examine both of these Phases under each scheme.

4.3.2 Models' Categorization

The are two orthogonal dimensions for the classification of the coordination schemes. The first dimension is determined by the entity that assemblies the sub-SLAs for the creation of the bundled one. Thus, we have:

- The **Distributed** approaches where each NSP bundles his own sub-SLAs with those of his neighbours'
- The **Centralized** approaches, where a central entity, such as a broker, gathers and assembles the SLAs

The second family is based on the entity that triggers the Service Composition phase. Thus, we have:

- The **Pull** approaches, where it is triggered by the buyer of the service and
- The **Push** approaches, where it is triggered by the providers (before a buyer's decision to purchase)

The combination of approaches from these two "orthogonal" dimensions, results in four coordination schemes that we describe below and two more, hybrid ones. We will describe the Publishing and the Service Composition Phases under each such scheme. Also according to the assumptions of the information available, each scheme may result in different pricing strategies for the participants.

4.3.2.1 The approaches

Distributed and Centralized approaches. These approaches are defined according to the entity that assembles the multiple sub-SLAs in order to construct a bundled one. In the centralized approaches there is a central entity, which communicates with every node that is willing to offer such a service. In the distributed approaches, the assembly is done by a node, either the buyer or the first or the last node on the chain. This difference also affects the information available to the participants. In the case of centralized approach information about the Network Capabilities or the SLA offers (from the Publishing or the Service Composition Phases respectively) is gathered to a specific entity. This entity is usually a joint venture, managed by all the participants, due to the fact that it has to be trusted from every entity in the federation. In the distributed approaches, there is no central entity, and thus the providers must be informed in some way about the network capabilities and the SLA offers.

Pull and Push approaches. These approaches are defined according to the entity that initiates the Service Composition Phase. Under the Pull approaches, the SLA offers start to be created after a buyer's request. In this case, the offers can be fully customized to buyer's needs. Under the Push approaches, a participant starts creating SLA offers and publishes them to others. He can publish them to:

- is neighbors that also participate
- to all participants through a notification board
- to one or several central entities
- to any other sub-set of participants

Thus, when the buyer becomes interested in purchasing a service the offers are ready to be bundled.

The combination of the approaches and the hybrid ones are depicted in Table 4.1.

4.3.2.2 Distributed Pull Model

The basic form of a Distributed Pull Model is presented in Figure 4.4. All the information needed is propagated in a distributed way; there is no central entity. Also, since it is a Pull model, the Service Composition Phase is triggered by the request of the buyer.

Publishing Phase. During this phase the participants propagate information to their neighbours about their Network Capabilities. The amount of information revealed and to which neighbours it is not fixed but can vary in different cases. This may affect though the pricing strategies of the participants and the

Table 4.1: Combination of the approaches

	Distributed	Per-Buyer Centralized	Fully Centralized
Pull	The buyer sends a request to the first NSP in the chain. NSPs propagate the request in their turn	The buyer sends requests to all NSPs in the chain. It combines the offers afterwards	Buyer sends a request to the facilitator, which in turn sends the sub-requests to the appropriate NSPs and gathers their offers
Push	NSPs propagate the final offers to their neighbors.	NSPs publish their final offers to catalogues. Buyer access those catalogues and combine the offers	NSPs publish their offers to the facilitator. When buyer asks for a service, the combination of offers is done.

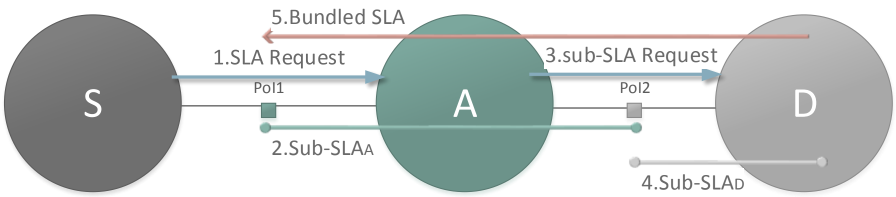

Figure 4.4: Distributed Pull Model: Service Composition Phase

service provision, as we will see in next section. The minimum set of information released concerns the **destinations** reached. This information can be also retrieved through the BGP tables. By knowing the destinations and each hop from a source to this destination different chains of participants can be created. Thus, in the next phase the buyer, that triggers it, would have to request the service from each of those chains. Revealation of more information to the neighbours assists the creation of more appropriate chains only, where the QoS level that they will be able to offer is known. Thus, in the next phase the buyer will request the same service from fewer chains and especially only from those that they can provide the QoS level requested. In this example, where we have only one chain, we suppose that D propagated to A his Network Capabilities and A in his turn, propagated the capabilities of his own network (to reach destinations in his own network) and the capabilities of both networks (A and D) together (thus those of the chain) for the destination in D's network. Of course, since the status of the networks changes frequently, periodically new information is released to the chains.

Service Composition Phase. This Phase is triggered by the buyer, when he requests from his neighbour a specific service. What he actually requests is the SLA for sending traffic from PoI1 to the destination in network D (1. SLA Request in Figure 4.4). This SLA includes the desirable QoS level and a price. Each participant in the chain after receiving an SLA request keeps the part that he will provide for the service to be offered and propagates the remaining part to the next provider in the chain (to be formed) as a request. Specifically in our example of Figure 4.4 the SLA-request is propagated to the first provider (A) that creates a new sub-SLA-request (3.sub-SLA Request) by reducing the price by the amount that he is willing to get paid and any other additive parameters of the SLA-request and/or agreeing with the concave ones. Note that the **additive** parameters are those that increase in each hop of the chain. Besides price, other such parameters are delay and jitter. On the other hand, a **concave** parameter is determined by its minimum value in the chain; the bandwidth of the connection is an important such parameter. When the sub-SLA-request reaches the destination (D), the service is indeed provided if this last provider agrees with the remaining price and QoS characteristics.

4.3.2.3 Distributed Push Model

The basic form of a Distributed Push Model is presented in Figure 4.5. Again in this model the information is propagated in a distributed way to all participants. The difference to the previous model is that the creation of SLA offers is done before the request of the buyer.

Publishing Phase. As mentioned before, during this phase the participant NSPs exchange information with other participants. Unlike the previous model it is not needed to reveal much information about the Network Capabilities, since the participants will send also the SLA offers before a buyer's request. The SLA

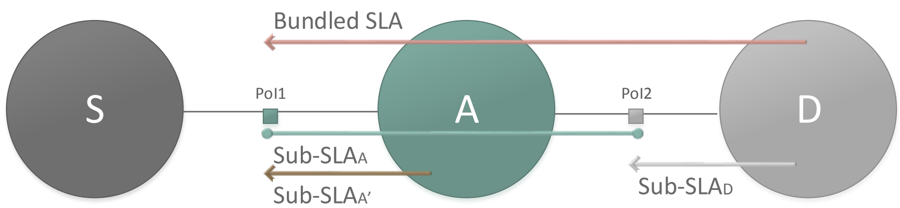

Figure 4.5: Distributed Push Model: Service Composition Phase

offer as mentioned above are a superset of the Network Capabilities since they also state the price of the service. The only information needed in this stage is the participants in order for an NSP to know where to propagate his offers.

Service Composition Phase Under this Phase, the participants create SLA offers, bundle them with those of their neighbours and propagate the bundled offers to the neighbour participants. In our case, shown in Figure 4.5, NSP D creates a sub-SLA offer with a price (sub-SLAD) advertising his on-net destinations and propagates it to NSP A. Of course he would also propagate this to any other neighbour participants if he had. NSP A in his turn propagates to S his sub-SLA (sub-SLAA') advertising his on-net destinations (within A). Also he may bundle a sub-SLA (sub-SLAA) with the SLA of NSP D and propagate the bundled SLA to S. Any other additive parameters will be increased accordingly. When the buyer needs such a service he knows the available destinations and prices for a QoS assured connectivity service to them.

4.3.2.4 Centralized Pull Model

As mentioned before in the centralized models there is an entity (e.g., a broker), that coordinates the publishing of offers by the participants as well as the formation of SLAs. An example is depicted in Figure 4.6.

Publishing Phase. As in the Distributed Pull Model, during this Phase the participants publish their network capabilities, but this time to a central entity. Thus, this entity is aware of the Network Capabilities of all NSPs of the community. Based on this information, the entity derives one or multiple NSP chains

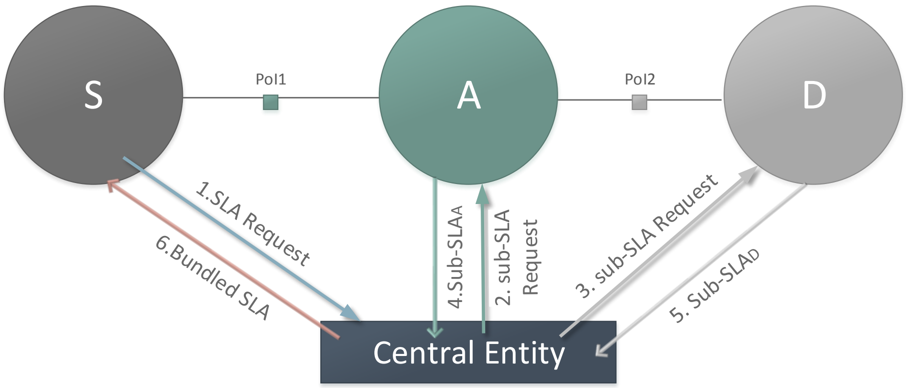

Figure 4.6: Centralized Pull Model: Service Composition Phase

that could potentially handle the buyer's request for PoI, destination and QoS characteristics.

Service Composition Phase. This Phase is triggered when the buyer requests from the central entity a bundled SLA. The central entity in its turn asks from each provider in the appropriate chains selected, according to the information it already has gathered from the previous phase, to offer a sub-SLA . After gathering the sub-SLAs and assembling them to one, the central entity provides the bundled SLA to the buyer. In our specific example, first S requests a bundled SLA from the central entity (1. SLA Request in Figure 4.6) and then the central entity requests from A and D the appropriate SLAs (2.sub-SLA Request, 3.subs-SLA Request) that when combined provide the bundled one. When A and D respond (4.Sub-SLAA, 5.Sub-SLAD), the central entity assembles the SLA and provides it to the buyer (6.Bundled SLA). If there are multiple possible offers, the scheme is flexible regarding the selection criteria of the entity. Such selection criteria may be:

- Minimising the total delay for the service (the delay has an upper bound)
- Maximizing the total number of services that can be actually offers - Maximizing the number of buyers' requests that are served
- Maximizing the profits of the NSPs

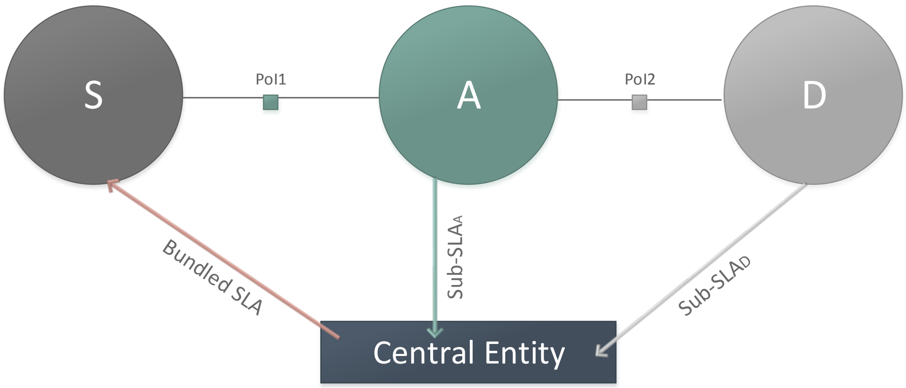

Figure 4.7: Centralized Push Model: Service Composition Phase

- Minimising the price that the buyer will pay
- Balancing the traffic caused by bundled offers to all available chain for the same pair source - destination

Alternatively, the buyer may decide which of the available offers best suits to him.

4.3.2.5 Centralized Push Model

This model is presented in Figure 4.7. Again it involves a central entity that gathers the necessary information.

Publishing Phase. During this Phase, the interested parties inform the central entity of their willingness to participate and their destinations. No more additional information is provided in this phase.

Service Composition Phase. All NSPs in the community inform the central entity about their sub-SLA offers. The buyer (S) communicates with the entity and reveals only the PoI, the destination and the QoS characteristics required for the specific end-to-end connectivity (SLA Request). The entity, based on the knowledge that it already has due to the Publishing Phase, the SLA offers and the SLA request, combines sub-SLA offers of those NSPs that form a chain from

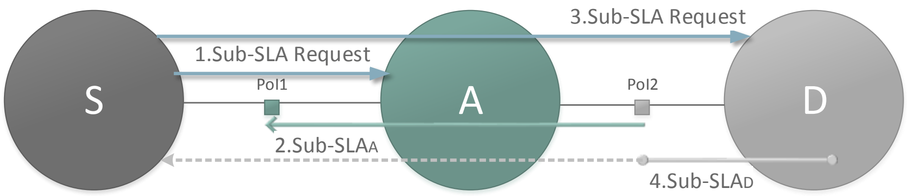

Figure 4.8: Per-Buyer Centralized Pull Model: Service Composition Phase

the source to the destination and announces them to the buyer. The buyer may accept or not one of the bundled SLA offer(s) depending on the characteristics of the QoS that he may want and the price of the bundled SLA.

4.3.2.6 Per-Buyer Centralized Pull Model

This is a hybrid coordination scheme derived from the centralised and distributed Pull ones. There is no central entity, but the buyer NSP plays this role. The motivation for this scheme was the privacy issues that may arise for the central entities. Indeed, we assume that central entities are neutral but in reality the providers are reluctant to reveal information about their networks in an entity, where there is no control of who is managing the it. That is why instead of a central entity, the buyer is gathering the information.

Publishing Phase. During the Publishing Phase all participants exchange information about their Network Capabilities and also, since the buyer has to contact each participant in a chain, information of how any provider can be reached is needed. Since the buyer will have to reach each provider without a proxy NSP, there must be a way of finding them. The announcements can be forwarded in a distributed way. However, the NSPs have to be properly motivated to propagate the information of their neighbours. We examine this issue in the next Section. Another possible and simple way is for the NSPs to set up a central place, as a portal, that is publicly accessible and all announcements are gathered there. Alternatively, there may be catalogues for each NSP, where they can upload their announcements.

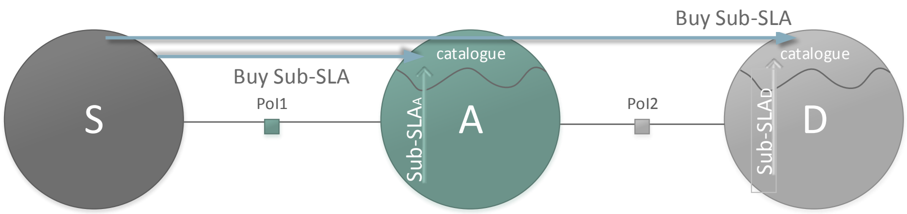

Figure 4.9: Per-Buyer Centralized Push Model

Service Composition Phase. When a buyer decides to purchase a bundled service asks each of the participants in the specific chain (1.Sub-SLA Request, 3.Sub-SLA Request), known from the Publishing Phase as in the Distributed Pull scheme, to provide him a sub-SLA offer (2.Sub-SLAA, 4.Sub-SLAD). The difference from the Distributed Pull Model is that the buyer accesses each participant on his own, without involving intermediate ones. In the particular case of Figure 4.8 the buyer asks NSPs A and D for the respective sub-SLAs and he bundles them by himself.

4.3.2.7 Per-Buyer Centralized Push Model

Publishing Phase. This Phase coincides with the Service Composition one.

Service Composition Phase In this Phase, the participants publish their SLA offers in their catalogues (see Figure 4.9). Then, the buyer accesses these catalogues to purchase sub-SLAs and bundles them himself. As opposed to the Distributed model, here the buyer buys the SLA offers from each NSP separately even if it is not directly connected to it.

4.4 Information Issues on Coordination models

The total price of the service, the revenue sharing among the NSPs (affected by means of the prices assigned to their sub-SLA offers) and the selection of the NSPs that will participate in satisfying a specific service request may differ across the models. These differences stem from the information set that is available to each participant and is formed during the Publishing Phase, as well as in the fact that a different entity makes the final selection of the optimal offer in each model.

Information Completeness Issues. In all models, the information available depends on the level of truthfulness of the NSPs participating, in accordance to the incentives of each of them. When the announcement of the Network Capabilities or the SLA-offers is done in a **distributed** way, hiding or strategic manipulation of parts of the information by the NSPs is possible. The simplest way for coordination w.r.t. information passing is for NSPs to propagate information to the direct neighbours who undertake to bundle it with their own and redistribute it. However, this approach allows for strategic behaviours. For example, a participant may decide not to propagate the information of some of its neighbours, e.g., excluding this way a competitor. Hence, fewer possible chains may be created, thus affecting the adversely social welfare of the community.

Also similar issues may arise in the propagation of pricing information. Transit providers that may participate in multiple chains could affect it. They may announce a higher price for a bundled SLA-offer to favour a chain over another where a competitor participates in. Furthermore, they may raise network neutrality issues by pricing more paths to specific destinations to favour other similar ones. For example if the destination is a known CDN provider, they may favour their own CDN, since as transit providers they can control the chain to the destination through price. Putting a high price in its part of the service an NSP increases also its profits if this offer is indeed purchased and put at the same time a higher risk of rejection of the offer. Walrand in [30] present similar problems and show that non-cooperative pricing strategies between providers may lead to unfair distribution of profit. On the other hand, in Centralized Models this may not be the case. If the central entity assumed to be neutral, which is typically the case inside a federation, all information revealed is not altered. The information issue of the Distributed schemes can be overcome by forming federations. In those federations, rules are enforced in order for information of the NSPs to be treated in equal terms. For example, a rule could be that the information must be flooded to all community members. Per-Buyer Centralized schemes suffer from the same problem as the Distributed ones. Even if NSPs publish their information in catalogues that can be accessed by every member and thus allowing equal access to information to all, a minimal set of information about the chains and how the NSPs can be reached has to be available to all participants in the community.

Service Composition Issues. The choice about the preferred offer that may be purchased can be made by a central entity or the buyer. The central entity may decide according to its own criteria on the final choice of which sub-SLA will form the bundled one. In such a case the entity can choose to maximize the expected social welfare. Related criteria may be the maximization of the number of buyers that can be satisfied, or of the utilization of the network or fairness citeria such as balancing the additional traffic for the service to different chains, balancing of the revenues of the NSPs etc. Also, if the resources of the NSPs do not suffice to serve all requests pending at some time, the central entity may prioritize them or take into account their emergence in decision making in order to move requests to the future. Alternatively, the central entity can choose the optimal offer by applying buyers' criteria, typically the lowest price. This would make the Centralized Models equivalent to the Distributed ones under this perspective, as mentioned in the Distributed and Per-Buyer Push schemes. An equivalent alternative that include the propagation of the available choices to the buyer who then makes the best decision for him. Indeed in these Distributed (and Per-NSP) schemes the buyer accepts or not the final offer(s) that are reaching it and thus it has the final choice.

Strategic Positions and Pricing Issues. In Distributed schemes, the pricing of SLAs is done in a sequential order. In Pull schemes, the maximum acceptable price is known and each provider subtracts from the total amount his part for the service provision. In Push schemes, each NSP prices his sub-SLA offers and propagates them to his neighbours, who add a price for their part. In such cases, the **position** of an NSP in the path to the destination may influence the price that it claims for its part of the service. Thus, certain NSPs may have an **advantage** in these coordination schemes due to their position; e.g. the first NSP in the chain. In Centralized schemes this can be avoided by no revelation of the SLA-offers to the other participants. This way the SLA offers are submitted simultaneously and thus advantageous positions are eliminated. However, central entities are not preferred by NSPs for privacy issues. Thus, even in the case of a Centralized scheme, it would be better to create a portal just for the announcements of the NSPs. If the announcements to the broker are public, then the scheme could be considered as equivalent to the Distributed one in the sense that the buyer decides which is the preferred offer and not a central entity. Thus, **an information issue is the consequences of the sequential pricing of a bundled-SLA, and has to be further investigated.**

Additive Parameters Splitting. The splitting of the additive parameters is a problem that arising in Pull schemes. Such parameters that fall into this category are delay, jitter and the price. The splitting, refers to the way that those parameters will be apportioned to the different NSPs in the chain. In Pull schemes the buyer sends an SLA request including those parameters. Under the Distributed Pull scheme, the splitting is done easily, since each NSP declares in its turn what part of the SLA will provide. Under the Centralized Pull scheme (and the Per-Buyer Centralized), this is not an easy task. The central entity could propagate the whole SLA request to all participants. Though, this way it is very difficult for them to coordinate. Indeed, in such a case each NSP should provide a sub-SLA and try to guess what offer the other providers make. On the other hand, if the sub-SLA requests are to be propagated to NSPs, the centralized entity must have full information about the state of the networks to decide on them. This is not possible due to privacy issues and this is another reason that **favours Distributed schemes**. Also, the central entity can propagate the whole SLA request to the first NSP and then propagate the sub-SLA request to the next in the chain etc. This way the scheme is equivalent to the Distributed Pull scheme.

Conclusions on Information Issues. The information issues discussed in the previous section concern the information asymmetry that may arise among the participants, the criteria under which the service composition is done, the pricing strategies that can be followed and the splitting of the additive parameters. All these issues may influence the offering of the service and the participants to the chain. Most of them although, can be dealt with success, since they can be equivalent with each other when the respective, to what we want to achieve, various options are chosen. However, due to the endogenous privacy problems of the Centralized schemes, the Distributed ones are preferred in practice by the NSPs. The main difference between them and the Centralized ones, is the sequential bidding for offering the service. This is the only issue that cannot be eliminated. In fact, this issue arises in two forms; i.e., under the Pull and under the Push schemes. In Pull schemes, the total acceptable amount is known to the NSPs, while in the Push ones it is not. In both schemes, strategic behaviours in pricing strategies arise. Thus, we continue our study with the analysis of these strategies and the investigation of the advantageous positions that may arise. In particular, we proceed with the mathematical formulation and analysis of two representative distributed models, a Push and a Pull one.

4.5 Mathematical Formulation of Coordination Models

In this section, we analyze the pricing strategies and advantageous positions that may rise in the Distributed Schemes. We also compare the models' efficiency in terms of the probability of the service being offered to a basic Collaborative model where the NSPs only cover their costs. For simplicity of the analysis, we consider a path with 3 NSPs.

4.5.1 Distributed Pull Model

As already described above, the buyer formulates an SLA request, including the price P_S that he offers to the NSPs. Note that this price is in general less than the buyer's utility (i.e., willingness-to-pay) V_S for the SLA, in order for him to acquire some positive net benefit; their exact relation is investigated later. Also, the costs of the respective NSPs for providing the service, are denoted as C_A and C_D. We also define the optimal prices P_A^* and P_D^* that the NSPs choose. When the first NSP in the chain (i.e., A) receives the request, it decides on the appropriate price P_A for its part of the SLA. Then, A propagates the sub-SLA as

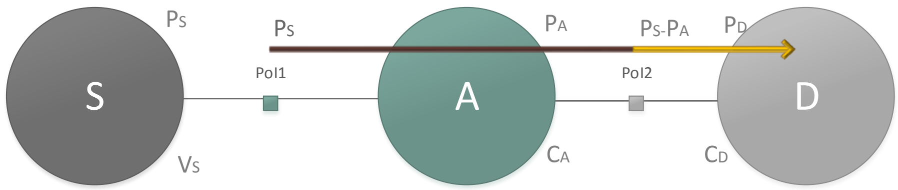

Figure 4.10: Distributed Pull Model Offers Passed

well as the remaining budget $P_S - P_A$ to the next NSP (i.e., D), who of course takes it all, since it is the last one in the simple path considered (Figure 4.10).

4.5.1.1 Full Costs' Information

Under the simplest assumptions for the Pull model, full information of costs is available to the NSPs participating in the chain. That is, the costs of the NSPs are known to each other. Then, the optimal choice of A will be $P_A^* = P_S - C_D$, if, of course, $P_S - C_D \geq C_A$. Then A propagates the sub-request to D, whose optimal and at the same time only possible price in order for the service to be provided, will be $P_D^* = C_D$. In such a case, the first NSP absorbs the whole surplus from the buyer's price if this makes him profitable, while the profit of D is zero. As already mentioned, a necessary condition for the transaction to take place, is that the sum of the costs of both NSPs has to be less or equal to the price that the buyer asks, i.e., $C_A + C_D \leq P_S$. Otherwise, there is no choice of prices summing to P_S that renders both NSPs profitable, which is necessary for each of them in order to participate. In fact, this restriction applies under any coordination model.

4.5.1.2 Incomplete Cost Information

Analysis of the Model. To make our assumptions on information availability less restrictive and more realistic, we assume that the costs of the NSPs are not precisely known to other NSPs. In particular, we assume that NSP A (resp. D) only knows the **distribution** of the cost C_D of the other NSP rather knowing its value (resp. C_A). Also, the two costs are assumed to be independent random variables. In order for A to agree to make the transaction, he has to choose a price P_A satisfying $C_A \leq P_A$ and $P_A \leq P_S$, while for D to agree, the offer passed to him by A satisfy $C_D \leq P_S - P_A$. Since A does not know the exact cost of D, it can only decide on the basis of the information on the distribution of C_D. A makes the first move by choosing P_A in order to **maximize its own expected profit**. This expected profit is given by the following expression:

$$\mathrm{E}[(P_A - C_A) \cdot 1(C_D \leq P_S - P_A)],$$

where $1(C_D \leq P_S - P_A)$ is the indicator function that equals 1 if the outcome $C_D \leq P_S - P_A$ applies and 0 otherwise. NSP A can only earn its profit if the condition $C_D \leq P_S - P_A$ does apply for the unknown for A cost of D (C_D). Since $(P_A - C_A)$ does not depend on C_D, we can rewrite the above expression as:

$$E[(P_A - C_A) \cdot 1(C_D \leq P_S - P_A)] = (P_A - C_A)\Pr[C_D \leq P_S - P_A].$$

This quantity is to be maximized by A under the following constraints to the choices for P_A: $P_A - C_A \geq 0$, $P_S - P_A \geq 0$. A necessary condition for the feasible set to be non-empty is $C_A \leq P_S$, which can be verified by A. Hereafter, we assume that this condition applies. Dealing with the probability $\Pr[C_D \leq P_S - P_A]$, we note that the upper bound of C_D is $P_S - P_A$. Thus, the maximization problem of A is rewritten as:

$$\max_{P_A}(P_A - C_A) \int_{C_D=0}^{P_S-P_A} f_c(C_D) dC_D. \tag{4.1}$$

In order to proceed with our analysis, and obtain concrete yet illustrative results, we assume that the costs C_A and C_D are continuous independent random variables that are uniformly distributed in the interval [0,C_{max}]. This is a pessimistic assumption, in the sense that the costs exhibit a high degree of randomness within their support. Hence, another upper bound of C_D due to its uniform distribution is C_{max}. Thus, for deriving the optimal expected profit of A in (4.1), the upper bound of the integral will be the tightest of the two constraints: $P_S - P_A \geq C_D$ and $C_{max} \geq C_D$. Thus, we obtain the following maximization problem:

$$\max_{P_A}(P_A - C_A)\int_{C_D=0}^{\min\{P_S-P_A,C_{max}\}}\frac{dC_D}{C_{max}}.$$

If $P_S - P_A \leq C_{max}$, then we rewrite the expected profits of A as:

$$\max_{P_A}(P_A - C_A)\frac{P_S - P_A}{C_{max}}$$

s.t. $P_A - C_A \geq 0$, $P_S - P_A \geq 0$. However, since we assumed that $P_S - P_A \leq C_{max}$ for the upper bound of the integral, we now have two lower bounds for P_A, i.e., $P_A \geq C_A$ and $P_A \geq P_S - C_{max}$. Thus, we have three different cases. Two of them are due to the two constraints, depending on which of the lower bounds of P_A is the tightest one, since $P_A \geq \max\{C_A, P_S - C_{max}\}$, when the upper bound of C_D is $P_S - P_A$. The third case results from the second upper bound of C_D, which is C_{max} in the integral above. Thus, we will solve the three optimization problems below:

Case 1

$$\max_{P_A}(P_A - C_A)\frac{P_S - P_A}{C_{max}} \tag{4.2}$$
$$\text{s.t. } P_S - P_A \geq 0,\ P_A - C_A \geq 0$$

Case 2

$$\max_{P_A}(P_A - C_A)\frac{P_S - P_A}{C_{max}} \tag{4.3}$$
$$\text{s.t. } P_S - P_A \geq 0,\ P_A + C_{max} - P_S \geq 0$$

Case 3

$$\max_{P_A}(P_A - C_A) \tag{4.4}$$
$$\text{s.t. } P_A - C_A \geq 0,\ P_S - C_{max} - P_A \geq 0.$$

The derivation of the optimal prices can be found in Appendix A. We summarize here the optimum points of all Cases for A and D in Table 4.2 :

Following the step of composition the offer, A propagates the sub-SLA and the remaining amount to D. This NSP, since it is the last in the chain, takes the

Table 4.2: Optimal Prices of A and D

P_S	P_A^*	$P_D^* = P_S - P_A^*$
$[0,\ 2C_{max} + C_A]$	$\frac{P_S+C_A}{2}$	$\frac{P_S-C_A}{2}$
$(2C_{max} + C_A, \infty)$	$P_S - C_{max}$	C_{max}

Table 4.3: Benefits of A and D

P_S	$\pi_A(C_A)$	$\pi_D(C_A, C_D)$
$[0,\ 2C_{max} + C_A]$	$\frac{P_S-C_A}{2}$	$\frac{P_S-C_A}{2} - C_D$
$(2C_{max} + C_A, \infty)$	$P_S - C_{max} - C_A$	$C_{max} - C_D$

whole remaining amount. Thus, its price P_D equals the difference between the price that the buyer proposed and the price that NSP A selected after solving its maximization problem, i.e. $P_D = P_S - P_A$. The actual prices of D are shown in Table 4.2. Thus, now we have the prices of NSPs A and D that have been chosen according to the scenario that NSP A chooses first his price, when the price of the buyer is known to him.

Given the optimal choices and the values of C_A and C_D, we can compute the actual benefits (i.e., profits) of A and D. Those are computed by the equations $\pi_A(C_A) = P_A^* - C_A$ and $\pi_D(C_A, C_D) = P_D^* - C_D$ and the results are shown in Table 4.3.

In Fig. 4.11, we present numerical results for the profits of NSPs A and D that participate in the chain, showing that A always gains more than D, which we will see that many times results to failure of the service provision. We compare the profits under different values of P_S/C_{max}. As seen in the legends, P_S takes the values C_{max}, $3/2C_{max}$, $2C_{max}$ and $3C_{max}$. For each such case, we select 100 random pairs of C_A and C_D from a uniform distribution in [0,1]. However, to derive the percentages below and the ratios of profits of A and D we ran the numerical simulation of the model 1000 times and we calculated the mean values. The x axis corresponds to the profits of A, while y axis corresponds to the profits of D, as calculated from the equations shown in Table 4.3 depending on the value of P_S. Cross spots depict the cases of (P_A, P_D) where the service is not provided, because D **refuses** it since its profits would have been negative. The

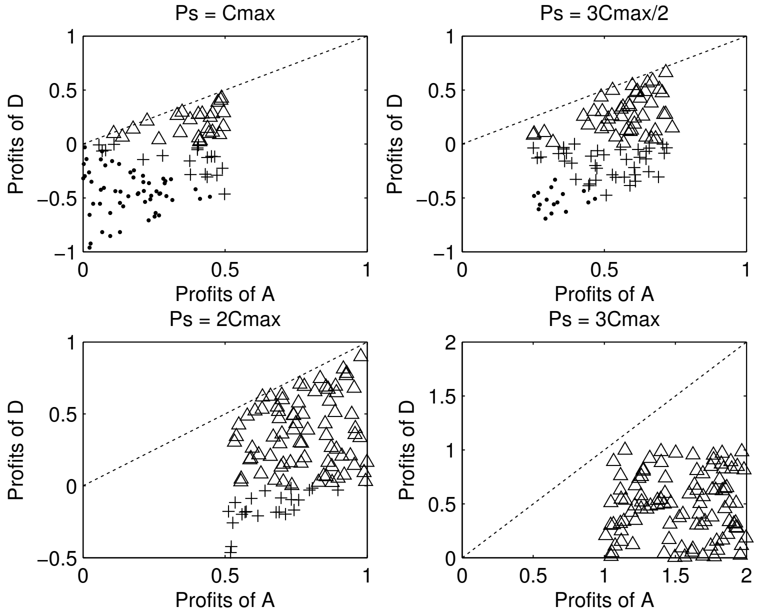

Figure 4.11: Profits of A and D for the Distributed Pull model

percentage of no service offered due to D's denial is 22.8% for $P_S = C_{max}$, 37.9% for $P_S = 1.5C_{max}$, 22.5% for $P_S = 2C_{max}$, and 0% for $P_S = 3C_{max}$. Also, dot spots depict the cases that the service cannot inherently **be provided** in any way because the sum of the costs of both NSPs exceeds P_S. Those percentages are 52.7% for $P_S = C_{max}$, and 13.3% when $P_S = 1.5C_{max}$. Of course this percentage is zero for higher values of P_S. As seen in the sub-figures, the service is given (triangle spots) with percentages 24.5%, 48.8%, 77.5% and 100% for the respective prices of P_S. The line $x = y$ has been included in the sub-figures to show the relation between P_A and P_D. P_A is always higher than P_D, hence all spots are always below this line. Of course, of actual interest are only the triangle spots, pertaining to cases where the service indeed is offered. NSP A gains on the average about 5.36, 5.99, 8.34 and 14.77 times more than D for the corresponding values of P_S, calculated by the average of ratios P_A/P_D. As the results clearly show, A gains an advantageous position over D by getting first more information from the buyer and acting first. This motivates A to bid as high as is optimal for him according to his estimations about D's costs, resulting many times to failure of offering the service since D's profits would have been negative.

Analysis of Efficiency. We can further evaluate the Distributed Pull model with unknown costs by quantifying this detrimental effect and showing the associated loss in efficiency. This loss can be presented by means of the discrepancy between the probability that the service is indeed offered under this model, where A follows its own optimal strategy, and the “ideal" Collaborative model, which is used as a benchmark. Under this Collaborative model, we assume that the NSPs collaborate with each other in order to provide the end-to-end service in all cases possible; thus, each NSP selects his own cost as a price, without trying to make any profits. In the case of Pull scheme though, since P_S is known to the NSPs they can also share the profits once D realizes that C_D does not exceed the offer $P_S - C_A$ propagated by A. Therefore, the probability that the service is achieved **collaboratively** equals $\Pr[C_D + C_A \leq P_S]$. The probability Pr[service] pertaining to the Collaborative model is obtained from the triangle distribution, since C_D, C_A are independent and follow identical uniform distributions. Thus, following some algebra, the expression of this probability is derived, as shown in 4.5. Random variable Z is the sum of the two random variables C_A, C_D, while a takes the values of P_S.

$$F_Z(z) = \begin{cases} 0 & \text{if } a < 0 \\ \frac{a^2}{2C_{max}^2} & \text{if } 0 \leq a < C_{max} \\ \frac{2a}{C_{max}} - \frac{a^2}{2C_{max}^2} - 1 & \text{if } C_{max} \leq a < 2C_{max} \\ 1 & \text{if } 2C_{max} \leq a \end{cases} \tag{4.5}$$

The proof of this expression is standard but also is presented in Appendix B for completeness reasons.

Furthermore, the probability that the service is indeed offered under the Pull model, where A follows its own optimal strategy, equals $\Pr[C_D \leq P_S - P_A]$. For the calculation of this probability, we substitute P_A with the optimal prices that we have derived in section 4.5.1.2. To calculate Pr[service] for the Pull model, we have to distinguish two cases, due to the expressions for P_A^*, shown in Table 4.2. However, in reality we have three cases due to the relation of P_S and C_A. Thus, for $P_S \leq 2C_{max}$,

$$\Pr[\text{service}] = \Pr[C_D + P_A^* \leq P_S] = \Pr[2C_D + C_A \leq P_S],$$

after the substitution of P_A^* with its expression from Table 4.2. This probability can be derived from the convolution of two non-identical uniform distributions. This is because for all possible values of C_A, P_S belongs to the interval $[0{,}2C_{max} + C_A]$, which implies $P_A^* = \frac{P_S + C_A}{2}$. Thus, the probability of the service being actually offered in this interval equals:

$$F_W(w) = \begin{cases} 0 & \text{if } a < 0 \\ \frac{a^2}{4C_{max}^2} & \text{if } 0 \leq a < C_{max} \\ \frac{a}{2C_{max}} - \frac{1}{4} & \text{if } C_{max} \leq a < 2C_{max} \\ \frac{-5C_{max}^2 + 6aC_{max} - a^2}{4C_{max}^2} & \text{if } 2C_{max} \leq a < 3C_{max} \\ 1 & \text{if } 3C_{max} \leq a \end{cases} \tag{4.6}$$

The derivation of $F_W(w)$ is straightforward and is given in Appendix C. For $P_S \leq 2C_{max}$ the probability of the service being provided is calculated from $F_W(w)$ above, because for all possible values of C_A, P_S belongs to the corresponding intervals. For $P_S \geq 3C_{max}$ the probability always equals 1. For $P_S \in [2C_{max}, 3C_{max}]$, we proceed differently, because the formula of P_A^* and thus of the conditional probability of the service being indeed provided given C_A, depends on the relation between P_S and C_A. Thus, we have to calculate:

- If $P_S \in [0,\ 2C_{max} + C_A]$, or $P_S - 2C_{max} \leq C_A$ then $\Pr[\text{service}]|\mathrm{C_A} = \Pr[2C_D + C_A \leq P_S|C_A]$
- If $P_S \in (2C_{max} + C_A,\ \infty)$, or $P_S - 2C_{max} > C_A$ then $\Pr[\text{service}] =$4.6.

Therefore we have:
$\Pr[\text{service}] = \mathrm{E}[\Pr[\text{service}|C_A]] = \int_{c=0}^{P_S - 2C_{max}} \frac{1}{C_{max}} dc + \int_{c=P_S-2C_{max}}^{C_{max}} \frac{1}{C_{max}} \Pr[C_D < \frac{P_S - c}{2}] dc =$

$\int_{c=0}^{P_S - 2C_{max}} \frac{1}{C_{max}} dc + \int_{c=P_S-2C_{max}}^{C_{max}} \frac{1}{C_{max}} \frac{P_S - c}{2C_{max}} dc =$

$= \frac{P_S - 2C_{max}}{C_{max}} + \frac{P_S(3C_{max} - P_S)}{2C_{max}} - \frac{C_{max}^2 - (P_S - 2C_{max})^2}{4C_{max}^2} = \frac{-5C_{max}^2 + 6P_S C_{max} - P_S^2}{4C_{max}^2}$

Summarizing we have:

$$F_W(w) = \Pr[\text{service}] = \begin{cases} 0 & \text{if } P_S < 0 \\ \frac{P_S^2}{4C_{max}^2} & \text{if } 0 \leq P_S < C_{max} \\ \frac{P_S}{2C_{max}} - \frac{1}{4} & \text{if } C_{max} \leq P_S < 2C_{max} \\ \frac{-5C_{max}^2 + 6P_S C_{max} - P_S^2}{4C_{max}^2} & \text{if } 2C_{max} \leq P_S < 3C_{max} \\ 1 & \text{if } 3C_{max} \leq P_S \end{cases} \tag{4.7}$$

In Fig. 4.12, we depict the probabilities of the service being offered according to the two models, as derived above, for all values of P_S in the interval $[0, 4C_{max}]$. The x axis corresponds to the values of P_S (normalized with C_{max}), while the y axis corresponds to Pr[service]. The dotted line refers to the Collaborative model while the solid line refers to the Distributed Pull model, where A acts selfishly, under the assumption that the buyer's offer equals his actual willingness to pay V_S; this assumption is relaxed in the next Subsection. Along the lines of the previous results, we observe that the probability of the service being indeed offered increases with P_S for both models, which is intuitively clear. In general, the curve for the Distributed model lies below that for the Collaborative one, thus implying that the service is more likely not to be offered under the former. This should have been intuitively expected, due to the selfish behaviour of NSP A. Also we observe that the difference between the Pr[service] in the Collaborative and the Distributed Pull models is increasing when P_S belongs to interval the $[0, 1.5C_{max}]$. For higher values of P_S the difference is decreasing until both curves reach 1 for $P_S = 2C_{max}$ for the Collaborative model and $P_S = 3C_{max}$ for the Distributed model. Hence, for large enough values of P_S, although A gains more than D, the service is offered always. On the other hand, for smaller values of P_S, the Distributed Pull model often fails to provide the service, resulting in loss of efficiency for the buyer and of attainable profits for the NSPs.

Shading bid and Probabilities Next, we analyse the optimal price offer for the buyer. Recall that the buyer is assumed to have a utility V_S for the bundled

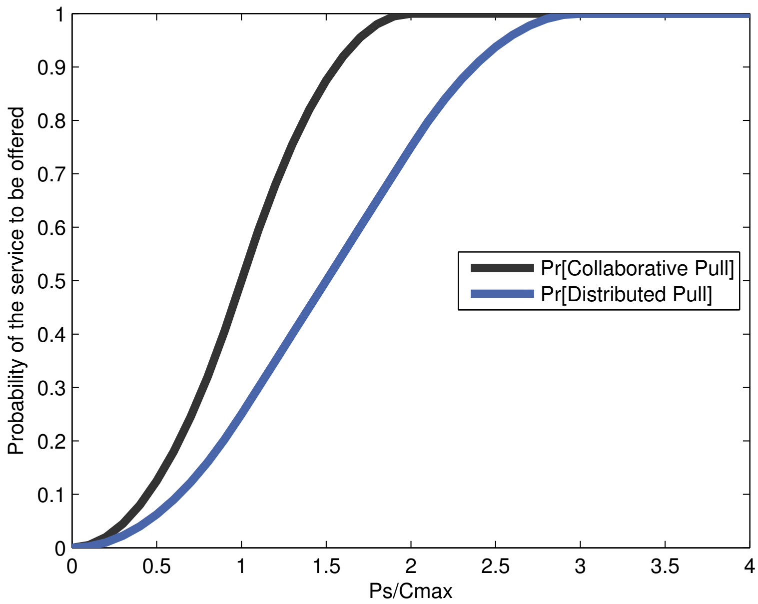

Figure 4.12: Comparison of Pr[service] under different models

service. However, he may not want to reveal this value to the NSPs but rather announce a lower price P_S. That is, the buyer **shades** his true value so that he attains a positive net benefit when he is indeed offered the service in this lower price. Below, we calculate the optimal P_S that the buyer should announce to the NSPs in order to maximize his expected net benefit, namely: $(V_S - P_S)\Pr[\text{service}]$. Thus, for each model (Distributed Pull and Collaborative), we analyse an appropriate Stackelberg game, where the buyer plays first, choosing his offered price, and then the NSPs play on this basis.

In particular, if the NSPs are using the **Collaborative model**, then according to our previous analysis, the buyer should choose P_S so as to maximize the following:

$$\max_{P_S}(V_S - P_S)\Pr[C_A + C_D \leq P_S],$$

in which the probability term is derived by means of convolution, as already explained in Appendix B. Thus, for each of the different expressions of the probability, we obtain different maximization problems. Note here that $V_S \geq P_S$ applies always.

Case 1: If $0 \leq P_S < C_{max}$:

$$\max_{P_S}(V_S - P_S)\frac{P_S^2}{2C_{max}^2} \tag{4.8}$$

$$\text{s.t.} V_S \geq P_S$$

In this case the optimal price is $P_S^* = \frac{2V_S}{3}$ and the maximum value that the buyer can gain by hiding it is $\frac{4V_S^3}{54C_{max}^2}$.
This case is valid when $P_S < C_{max} \Leftrightarrow \frac{2V_S}{3} < C_{max} \Leftrightarrow V_S < \frac{3C_{max}}{2}$.
Thus, if $0 \leq V_S < \frac{3C_{max}}{2}$, then $0 \leq P_S < C_{max}$ and optimal $P_S^* = \frac{2V_S}{3}$.

Case 2: If $C_{max} \leq P_S < 2C_{max}$:

$$\max_{P_S}(V_S - P_S)(\frac{2P_S}{C_{max}} - \frac{P_S^2}{2C_{max}^2} - 1) \tag{4.9}$$

$$\text{s.t.} V_S \geq P_S$$

In this case we have three possible solutions and thus there are three possible points:

1. C_{max},
2. $\frac{2V_S + 8C_{max} + \sqrt{\Delta}}{6}$
3. $\frac{2V_S + 8C_{max} - \sqrt{\Delta}}{6}$

The point $P_S^* = \frac{2V_S + 8C_{max} + \sqrt{\Delta}}{6}$ is not valid since this value exceeds the interval that P_S belongs to. Note that:

$$\Delta = 4V_S^2 - 16V_S C_{max} + 40C_{max}^2$$

The respective maximum values of 4.9 are:

1. $\frac{V_S - C_{max}}{2}$,
2. $(V_S - P_S)(\frac{2P_S}{C_{max}} - \frac{P_S^2}{2C_{max}^2} - 1)$

The second maximum value will always be greater than the first one. To show that we have to prove that: $\frac{V_S - C_{max}}{2} < (V_S - P_S)(\frac{2P_S}{C_{max}} - \frac{P_S^2}{2C_{max}^2} - 1)$.

This is a rather difficult thing to do. However, $1/2 \leq \frac{2P_S}{C_{max}} - \frac{P_S^2}{2C_{max}^2} - 1 < 1$ for each value of P_S in the interval $[C_{max}\ 2C_{max}]$. Its minimum value is 0.5 when $P_S = C_{max}$. At this point $\frac{V_S - C_{max}}{2} = (V_S - P_S)(\frac{2P_S}{C_{max}} - \frac{P_S^2}{2C_{max}^2} - 1)$, while for all the others the second value is greater since $V_S - P_S > V_S - C_{max}$ is always true due to the $C_{max} < P_S$.

Also, according to the intervals this case is valid when $\frac{3C_{max}}{2} \leq V_S < \infty$. Thus, if $\frac{3C_{max}}{2} \leq V_S < \infty$ then $C_{max} \leq P_S < 2C_{max}$ and the optimal point is $P_S = \frac{2V_S + 8C_{max} - \sqrt{\Delta}}{6}$.

Case 3: If $2C_{max} \leq P_S$:

$$\max_{P_S}(V_S - P_S) \cdot 1 \tag{4.10}$$

$$\text{s.t.} V_S \geq P_S$$

In this case the optimum price is $P_S^* = 2C_{max}$ and the maximum gain of the buyer is $V_S - 2C_{max}$. However, this point is not considered as optimal since for every $V_S \geq \frac{3C_{max}}{2}$ the optimal P_S is always $P_S = \frac{2V_S + 8C_{max} - \sqrt{\Delta}}{6}$.

The calculation of the optimal points is given in Appendix D.

We proceed the same way for the **Distributed Pull** model, where the buyer solves the following optimization problem:

$$\max_{P_S}(V_S - P_S)\Pr[P_A^* + C_D \leq P_S]$$

or

$$\max_{P_S}(V_S - P_S)\Pr[C_A + 2C_D \leq P_S],$$

by substituting the value of P_A^*. We have already studied this probability in 4.5.1.2; its form is given below, while the proof is given in Appendix C. Let us say that the random variable $C_A + 2C_D$ is denoted with W and its values with w. Also P_S has a known value. Then, according to Eq. 4.7, the cumulative distribution function of the probability is:

$$F_W(w) = \begin{cases} 0 & \text{if } P_S < 0 \\ \frac{P_S^2}{4C_{max}^2} & \text{if } 0 \leq P_S < C_{max} \\ \frac{P_S}{2C_{max}} - \frac{1}{4} & \text{if } C_{max} \leq P_S < 2C_{max} \\ \frac{-5C_{max}^2+6P_SC_{max}-P_S^2}{4C_{max}^2} & \text{if } 2C_{max} \leq P_S < 3C_{max} \\ 1 & \text{if } 3C_{max} \leq P_S \end{cases}$$

Since the cumulative distribution function of the probability is given by multiple formulae, depending to the value of P_S, we solve the maximization problem separately for each case.

Case 1: If $0 \leq P_S < C_{max}$:

$$\max_{P_S}(V_S - P_S)\frac{P_S^2}{4C_{max}^2} \tag{4.11}$$

$$\text{s.t.} V_S \geq P_S$$

In this case the optimal price is $P_S^* = \{\frac{2V_S}{3}\}$ and the maximum value that the buyer can gain by hiding is $\frac{V_S^3}{27C_{max}^2}$. According to the constraint of P_S we calculate the interval of V_S. Thus, if $0 \leq V_S < \frac{3C_{max}}{2}$, then the optimal point for P_S is $P_S^* = \{\frac{2V_S}{3}\}$.

Case 2: If $C_{max} \leq P_S < 2C_{max}$:

$$\max_{P_S}(V_S - P_S)(\frac{P_S}{2C_{max}} - \frac{1}{4}) \tag{4.12}$$

$$\text{s.t.} V_S \geq P_S$$

In this case we have two possible points:

1. C_{max},
2. $\frac{2V_S+C_{max}}{4}$

The respective maximum values of 4.12 are:

1. $\frac{V_S - C_{max}}{4}$,
2. $\frac{V_S^2}{8C_{max}} - \frac{V_S}{8} + \frac{C_{max}}{32}$

In this case we prove that the second maximum value is always greater or equal to the first one, i.e., $\frac{V_S^2}{8C_{max}} - \frac{V_S}{8} + \frac{C_{max}}{32} \geq \frac{V_S - C_{max}}{4}$. Also, due to the constraints of the P_S we may say that if $\frac{3C_{max}}{2} \leq V_S < \frac{7C_{max}}{2}$, then $C_{max} \leq P_S < 2C_{max}$ and the optimal point is $\frac{2V_S + C_{max}}{4}$.

Case 3: If $2C_{max} \leq P_S \leq 3C_{max}$:

$$\max_{P_S}(V_S - P_S)\frac{-5C_{max}^2 + 6P_SC_{max} - P_S^2}{4C_{max}^2} \tag{4.13}$$

$$\text{s.t.} V_S \geq P_S$$

In this case we have two possible points:

1. $2C_{max}$,
2. $\frac{2V_S + 12C_{max} \pm \sqrt{\delta}}{6}$

Note that $\delta = 4V_S^2 - 24V_SC_{max} + 84C_{max}^2$. The point $P_S^* = \frac{2V_S + 12C_{max} + \sqrt{\delta}}{6}$ is not valid due to the constraint of the interval of the P_S. The respective maximum values of 4.13 are:

1. $\frac{3(V_S - 2C_{max})}{4}$,
2. $(V_S - P_S)\frac{-5C_{max}^2 + 6P_SC_{max} - P_S^2}{4C_{max}^2}$

In this case, again as in Collaborative Shading model, we cannot prove easily which value is always greater than the other. However, we can show that $3/4 \leq \frac{-5C_{max}^2 + 6P_SC_{max} - P_S^2}{4C_{max}^2} < 1$ when $2C_{max} \leq P_S \leq 3C_{max}$. Thus, since $V_S - P_S \geq V_S - 2C_{max}$ the second maximum value will always be greater.

Also, we can calculate the values of V_S for those values of P_S. For each $\frac{7C_{max}}{2} \leq V_S < \infty$, $2C_{max} \leq P_S \leq 3C_{max}$ and the optimal point is $\frac{2V_S + 12C_{max} - \sqrt{\delta}}{6}$.

Case 4: If $3C_{max} \leq P_S$:

$$\max_{P_S}(V_S - P_S) \cdot 1 \tag{4.14}$$

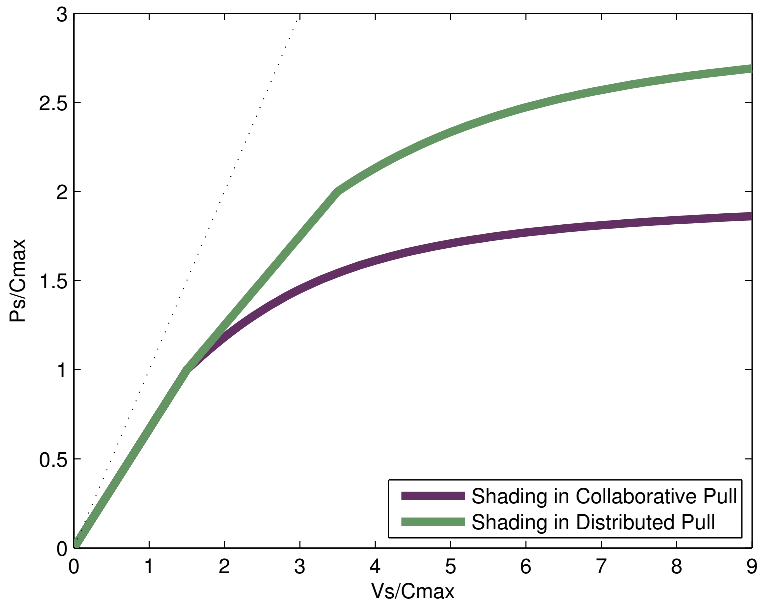

Figure 4.13: Relation of the truthful and the optimal prices for shading bid

$$\text{s.t.} V_S \geq P_S$$

In this case the optimum price is $P_S^* = 3C_{max}$ and the maximum gain of the buyer is $V_S - 3C_{max}$. However, for every V_S the preferred optimal point is lower than $3C_{max}$.

The calculation of these optimal points can be found in Appendix D. The relation between the optimal values that the buyer may announce to the NSPs and his real valuation for the service under both the Distributed Pull and the Collaborative Pull is shown in Figure 4.13. For each V_S, the price that the buyer announces in the Collaborative model is lower than or equal to that in the Distributed Pull model (equality applies for low values of namely below $8Cmax/5$) This is due to the selfish behaviour of NSP A, which affects the buyer's prices too. In order for the buyer to have better chances to be offered the service, he should announce a higher price under the Distributed Pull model. The position of the two curves relatively with line $x = y$ indicates the large difference between the utility V_S and the corresponding prices P_S offered. Note that in the interval $[\frac{3C_{max}}{2}, \frac{8C_{max}}{5}]$ P_S is fixed and equal to C_{max}. At that region both lines are horizontal to the axis x but due to the small scale of the figure (Figure 4.13) this is not shown clearly.

Having derived the optimal prices announced by the buyer, we can calculate the probability of the service to be indeed offered under each optimal point in both the Collaborative and Distributed Pull models, given respectively by $\Pr[C_A + C_D \leq P_S]$ and $\Pr[P_A^* + C_D \leq P_S]$ where the different values of P_S were calculated before and those of P_A^* in subsection 4.5.1.2. Let us begin with $\Pr[C_A + C_D \leq P_S]$. We substitute the values of P_S to the probability according the values of V_S, which gives us four different cases.

Case 1: If $V_S < \frac{3C_{max}}{2}$ then $P_S < C_{max}$ and thus its optimal value is $P_S = \frac{2V_S}{3}$. From Eq. 4.5 we have:

$$\Pr[C_A + C_D \leq \frac{2V_S}{3}] = F_Z[\frac{2V_S}{3}] = \frac{2V_S^2}{9C_{max}^2}$$

Case 2: If $\frac{3C_{max}}{2} \leq V_S < \infty$ then $C_{max} \leq P_S < \frac{3C_{max}}{2}$ and thus the optimal value is $P_S = \frac{2V_S + 8C_{max} - \sqrt{4V_S^2 - 16V_S C_{max} + 40C_{max}^2}}{6}$. Hence, we have:

$$\Pr[C_A + C_D \leq \frac{2V_S + 8C_{max} - \sqrt{\Delta}}{6}] =$$
$$F_Z[\frac{2V_S + 8C_{max} - \sqrt{\Delta}}{6}] =$$
$$\frac{-V_S^2 + 4V_S C_{max} + 2C_{max}^2 + (V_S - 2C_{max})\sqrt{\Delta}}{9C_{max}^2},$$

where $\Delta = 4V_S^2 - 16V_S C_{max} + 40C_{max}^2$.

Similarly for the $\Pr[P_A^* + C_D \leq P_S] = \Pr[C_A^* + 2C_D \leq P_S]$ we have again multiple cases according to the values of V_S and P_S. In this case we use Eq. 4.7.

Case 1: If $V_S < \frac{3C_{max}}{2}$ then $P_S < C_{max}$ and thus the optimal point is $P_S = \frac{2V_S}{3}$. Thus, the probability is:

$$\Pr[C_A + 2C_D \leq \frac{2V_S}{3}] = F_W[\frac{2V_S}{3}] = \frac{V_S^2}{9C_{max}^2}$$

Case 2: If $\frac{3C_{max}}{2} \leq V_S < \frac{7C_{max}}{2}$ then $C_{max} \leq P_S < 2C_{max}$ and the only possible optimal value is $P_S = \frac{2V_S + C_{max}}{4}$. Hence we have:

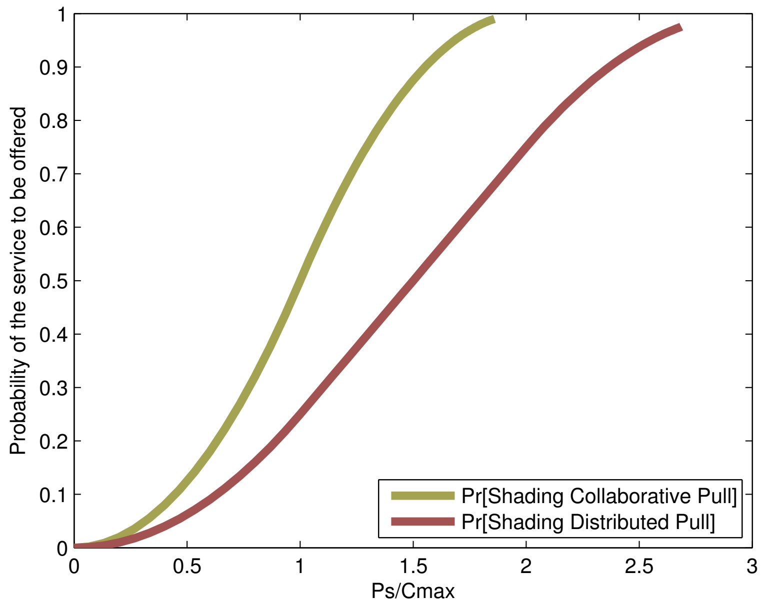

Figure 4.14: Comparison of Pr[service] under Shading models

$$\Pr[C_A + 2C_D \leq \frac{2V_S + C_{max}}{4}] = F_W[\frac{2V_S + C_{max}}{4}] = \frac{2V_S - C_{max}}{8C_{max}}$$

Case 3: If $\frac{7C_{max}}{2} \leq V_S < \infty$ then $2C_{max} \leq P_S < 3C_{max}$. This means that the possible optimal value is $\frac{2V_S+12C_{max}-\sqrt{4V_S^2-24C_{max}V_S+84C_{max}^2}}{6}$. Hence the probability is:

$$\Pr[C_A + 2C_D \leq \frac{2V_S + 12C_{max} - \sqrt{4V_S^2 - 24C_{max}V_S + 84C_{max}^2}}{6}] =$$

$$F_Z[\frac{2V_S + 12C_{max} - \sqrt{4V_S^2 - 24C_{max}V_S + 84C_{max}^2}}{6}] =$$

$$\frac{-5C_{max}^2 + 2C_{max}(V_S + 6C_{max} - \sqrt{\Theta}) - \frac{1}{9}(V_S + 6C_{max} - \sqrt{\Theta})^2}{4C_{max}^2}$$

where $\Theta = V_S^2 - 6V_SC_{max} + 21C_{max}^2$.

Figure 4.14 depicts the probabilities that the service is indeed offered under the Collaborative and the Distributed Pull models when the buyer performs the

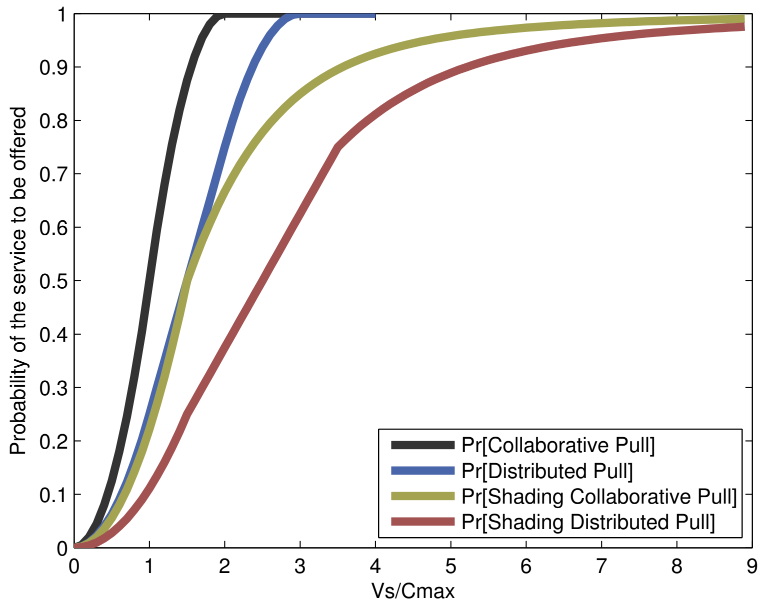

Figure 4.15: Comparison of Pr[service] under Pull and Shading Pull models

optimal for him bid shading. The green line corresponds to the Shading Collaborative model, while the red one to the Shading Distributed Pull. As indicated by the mathematical analysis the probabilities never reach one, since P_S under every value of V_S never exceeds an upper bound in both models. The values of V_S taken for these plot are as high as $9C_{max}$, but the values of P_S are less than $2C_{max}$ for the Shading Collaborative and less than $3C_{max}$ for Shading Distributed Pull. In Figure 4.15 we depict the probabilities of the service being offered under the Pull models and the Shading Pull models. The Shading Pull ones are, as the mathematical analysis also showed, less efficient than the Pull ones. Note here that the x axis corresponds to V_S values. For the Pull models theses values coincide with the price P_S that the buyer announces to the NSPs. For the Shading models these values define what the buyer is willing to pay and they do not coincide with the prices that he announces. In fact if we plot the probabilities of the service being offered but taking into account the prices announced under each model then the Collaborative Pull and the Distributed Pull plots coincide with the Shading Collaborative Pull and the Shading Distributed Pull accordingly. However the latter ones never reach one.

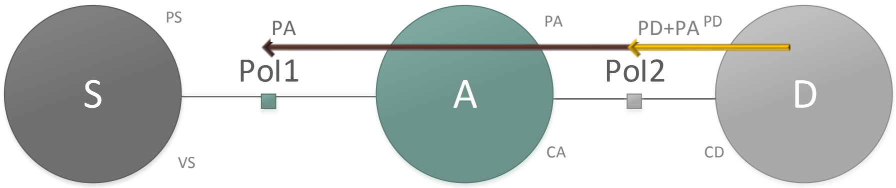

Figure 4.16: Distributed Push Model

4.5.2 Distributed Push Models

4.5.2.1 NSP Costs Known to others

——————————————Sto sxima na einai mikra ta gramamta——————

—————— As in the previous analysis, We assume that we have only three NSPs in the chain; thus, the buyer S requests from A an SLA to connect to D. A after deciding P_A propagates SLA and P_A to D. D decides its own price P_D and they propagate $P_A + P_D$ to the buyer, who takes the offer or not. This process is shown in Figure 4.16. For A and D to agree to make the transaction their prices have to exceed their costs (C_A, C_D). Also $P_A + P_D \leq P_S$ and $C_A + C_D \leq P_S$, where P_S is the price that the buyer is willing to pay, should apply in order for the service to be ultimately provided. Also, both costs are here assumed to be known to both the providers who only know the distribution of P_S. The problem that the NSPs A and D have to solve is:

$$\max E\left[(P_*(C_*) - C_*) * 1\left(Service\ is\ provided\right)\right]$$

The interaction of A and D corresponds to a Stackelberg game. In order to proceed with the analysis of a simple yet illustrative case, we assume that P_S follows a uniform distribution and thus $P_S \sim U[0, P_{Smax}]$. Next, we outline the analysis of this model. Since A chooses its price first it will choose P_A such that $0 \leq P_A + C_D \leq P_{Smax}$. It can avoid the case of $P_A + C_D \geq P_{Smax}$ (where the service is surely not provided) since it is assumed to know C_D too. ——————

——————————————————————- (Note that A in practice can be assumed to have some knowledge on the cost of D if e.g.

they have similar infrastructures. Of course, the assumption that this knowledge is accurate is only adopted for simplicity of the model.) Once P_A is announced to D, then the only feasible and at the same time meaningful choice for P_D is to satisfy: $P_A + P_D \leq P_{Smax}$. Solving the above maximization problem for D we obtain the optimal choice for him (P_D^*). Subsequently, we solve the maximization problem of A. The value of P_D^* is not known to A. It comes as a result of the choice of P_A by A. However, A can make use of the expression of P_D^* and then calculate P_A on this basis. A will choose P_A such that $P_D^* + P_A \leq P_{Smax}$. The expressions for the optimal points of A and D are derived in Appendix E. Making use of those optimal choices, we can derive the actual profits of A and D in the cases that the service is indeed provided

Comparison of the Collaborative and the Distributed Push with known costs. In the table below (4.4), we show some numerical values of profits obtained and we compare them to the Collaborative scenario. As presented and also proved in closed form the profits of A in the Distributed Pull model are always higher than in the Collaborative one and also double those of D. Also the third row shows a case of a failure of service provision under the Distributed model in contrast to the Collaborative one. The last row shows a failure of both models due to a low price of the buyer.

Table 4.4: Comparison of Actual Profits of A and D

(C_A, C_D, P_S)	Collaborative Model	Distributed Pull Model	
	Both	A	D
$(0.043, 0.169, 0.649)$	0.218	0.394	0.197
$(0.113, 0.030, 0.939)$	0.387	0.417	0.208
$(0.075, 0.054, 0.531)$	0.200	-	-
$(0.547, 0.138, 0.149)$	-	-	-

Also we can evaluate this model by showing the loss in efficiency. This loss can be quantified by comparing: a) the probability $\Pr[P_D^* + P_A^* \leq P_S]$ (see eq. 4.15) that the service is achieved under this model, where A and D follow their own optimal strategies (P_A^*, P_D^*); and b) the probability $Pr[C_D + C_A \leq P_S]$ (see eq. 4.16) that a service is achieved collaboratively. Thus, when the NSPs act selfishly (Distributed Pull model) there is a huge loss in efficiency, resulting in a reduction of the probability that the service is offered by a factor of 4.

$$\Pr[P_D^* + P_A^* \leq P_S] = \Pr[\frac{3P_{Smax} + C_A + C_D}{4} \leq P_S] = \frac{P_{Smax} - C_A - C_D}{4P_{Smax}} \quad (4.15)$$

$$\Pr[C_D + C_A \leq P_S] = 1 - \Pr[P_S \leq C_D + C_A] = \frac{P_{Smax} - C_A - C_D}{P_{Smax}} \quad (4.16)$$

4.5.2.2 Unknown Costs

Model and Analysis of Strategies. Under this model we relax our costs assumptions. Again, for A to agree to make the transaction $C_A \leq P_A$ should apply and for D to agree to make the transaction $C_D \leq P_D$ should apply. In general $P_A + P_D \leq P_S$ should apply in order for the service to be ultimately provided (i.e., for the SLA to be accepted by the buyer), for which a necessary condition is $C_A + C_D \leq P_S$. Also, P_S is now only known to the buyer and unknown to the providers, who only know its distribution. Note that in the present case P_S essentially coincides with the buyer's willingness-to-pay V_S, since it is not announced. Furthermore, we assume that only the distribution of the cost of each NSP is known to the other participants. A chooses its price first and then propagates it to D, who then solves the following optimization problem:

$$\max_{P_D} \mathrm{E}[(P_D - C_D) \cdot 1(\text{service})],$$

where 1(service) is the indicator function that equals 1 if the service is indeed offered (i.e., if $P_A + P_D \leq P_S$) and 0 otherwise. The above problem is equivalent to the following:

$$\max_{P_D} (P_D(C_D; P_A) - C_D) \Pr[P_A + P_D(C_D; P_A) \leq P_S],$$

where P_D is a function of P_A and C_D such that $P_D \geq C_D$. Knowing how D will act, A takes this into account, when it chooses its own price first by solving the following optimization problem:

$$\max_{P_A} \mathrm{E}[(P_A(C_A) - C_A) \cdot 1(\text{service})], \text{or}$$

$$\max_{P_A} (P_A(C_A) - C_A)\Pr[P_A(C_A) + P_D(C_D; P_A) \leq P_S],$$

where P_A is a function of C_A, such that $P_A \geq C_A$. Hence, the model for the interaction of A and D is again a Stackelberg game. In order to proceed with our analysis, and obtain concrete yet illustrative results, we again assume that the costs C_A and C_D are independent and uniformly distributed in the interval $[0,\, C_{max}]$. Also, we preserve the assumption that P_S is uniformly distributed in the interval $[0,\, P_{Smax}]$. This is a pessimistic assumption, in the sense that the price exhibits a high degree of randomness within its support. Moreover, this assumption implies the following: once the NSPs announce the total price, the expected total “quantity" of services actually offered is clearly a linear function of that price with negative slope. Thus, essentially the NSPs face a linear demand function in the market, with the twist that each buyer either buys one “unit" or none, but never more.

We will begin our analysis from D. Before D decides, NSP A will have already chosen the value of P_A.

If $P_{Smax} \geq P_A + C_D$ applies, it is possible, but not certain that the service will be provided. On the other hand, the service will certainly not be provided if this condition is violated. The only feasible and at the same time meaningful choice is for D to choose P_D so as to satisfy: $P_A + P_D \leq P_{Smax}$. However, this is possible only if $P_A + C_D \leq P_{Smax}$, which is a condition verifiable by D. The probability of the service being offered, as estimated by D in this case, is:

$$\Pr[P_A + P_D(C_D) \leq P_S] = \int_{P_A + P_D(C_D)}^{P_{Smax}} \frac{1}{P_{Smax}} dP_S = \frac{P_{Smax} - P_A - P_D(C_D)}{P_{Smax}}.$$

The calculation of the optimal choice of D can be found in Appendix F and is equal to $P_D^* = \frac{P_{Smax} - P_A + C_D}{2}$ if the condition $P_{Smax} \geq P_A + C_D$ actually applies. The optimal value for D that we discussed in the previous section is not known to

A. It comes as a result of the choice of P_A by A, combined with the value of C_D, which is known to D but not to A. However, A knows the formula of P_D^*; and the fact that it is possible, but not certain, that the service will be provided if $P_{Smax} \geq P_A + C_D$. On the other hand, the service will certainly not be provided if this condition is violated. Since NSP A does not know the value of C_D, but only its distribution, A should take this undesirable possibility into account. Thus, for a given value of P_A the probability of the service being offered is: $\Pr[\text{service}] = \mathrm{E}[\Pr[\text{service}|C_D]] = \mathrm{E}[\Pr[P_{Smax} \geq P_A + C_D \text{ and } P_A(C_A) + P_D^* \leq P_S|C_D]] = \mathrm{E}[\Pr[P_A(C_A) + P_D^* \leq P_S|P_{Smax} \geq P_A + C_D \text{ and } C_D]\Pr[P_{Smax} \geq P_A + C_D|C_D]] =$

$$\mathrm{E}[E[\frac{P_{Smax} - P_D^* - P_A}{P_{Smax}} \cdot 1[C_D \leq P_{Smax} - P_A]|C_D]], \tag{4.17}$$

where all expectations above are taken w.r.t the distribution of C_D. Replacing $P_D^* = \frac{(P_{Smax} - P_A + C_D)}{2}$, we obtain:

$$\Pr[\text{service}|C_D] = \frac{P_{Smax} - P_A - C_D}{2P_{Smax}}.$$

This expression is applicable of course only for those C_D such that $C_D \leq P_{Smax} - P_A$, and provided that $P_A < P_{Smax}$. For the other values of C_D, the indicator function in 4.17 vanishes and hence so does $\Pr[\text{service}|C_D]$. We distinguish two cases: 1) the value of P_A is small enough, so that $C_{max} \leq P_{Smax} - P_A$ and 2) the value of P_A is larger, so that $C_{max} \geq P_{Smax} - P_A$. The condition $C_D \leq P_{Smax} - P_A$ applies for all C_D. Also, the expectation involved in the $\Pr[\text{service}|C_D]$ is obtained by integrating with respect to the uniform distribution of C_D in the entire interval $[0, C_{max}]$. Otherwise, the upper limit of the integral is $P_{Smax} - P_A$. Thus, we can now maximize the objective function of NSP A under both cases.

$$max_{P_A}(P_A(C_A) - C_A)Pr[service|C_D]$$

To summarize we conclude to the maximum points and the actual profits at those points, of A and D.

- If $P_{Smax} - C_A \leq \frac{3C_{max}}{2} \rightsquigarrow P_A^* = \frac{2C_A + P_{Smax}}{3} \rightsquigarrow \pi_A(P_A^*) = \frac{P_{Smax} - C_A}{3}$
  - In this case if $P_{Smax} \geq P_A^* + C_D$ or $P_{Smax} - C_A \geq \frac{3C_D}{2} \rightsquigarrow P_D^* =$

Table 4.5: Profits of A and D

$P_{Smax} - C_A$	$Prof_A(C_A)$	$Prof_D(C_D)$
$[0, \frac{3C_D}{2}]$	0	0
$(\frac{3C_D}{2}, \frac{3C_{max}}{2}]$	$\frac{M}{3}$	$\frac{2M-3C_D}{6}$
$(\frac{3C_{max}}{2}, \infty)$	$\frac{2M-C_{max}}{4}$	$\frac{2M-4C_D+C_{max}}{8}$

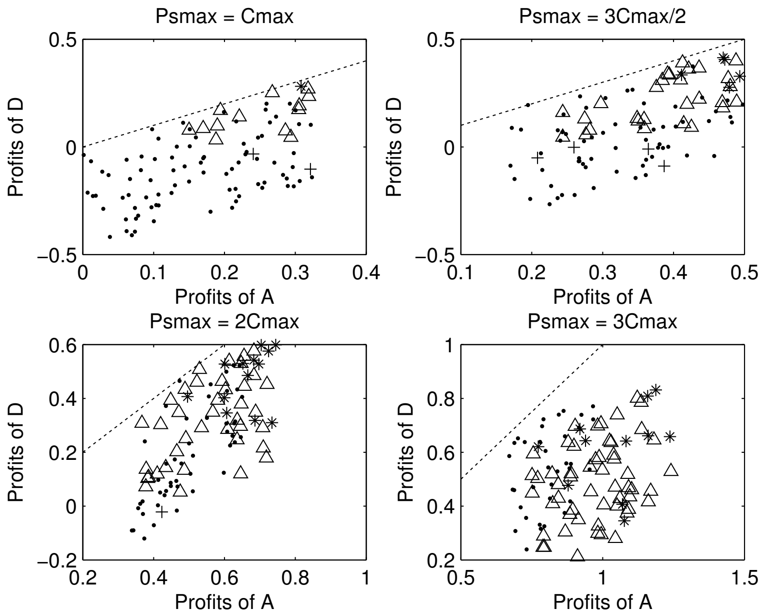

Figure 4.17: Profits of A and D in the Distributed Push Model for 100 random pairs of C_A and C_D for each case of P_S.

$$\frac{P_{Smax}-P_A^*+C_D}{2} = \frac{2P_{Smax}-2C_A+3C_D}{6} \rightsquigarrow pi_D(P_D^*) = \frac{2P_{Smax}-2C_A-3C_D}{6}$$

- If $P_{Smax}-C_A \geq \frac{3C_{max}}{2} \rightsquigarrow P_A^* = \frac{2C_A+2P_{Smax}-C_{max}}{4} \rightsquigarrow \pi_A(P_A^*) = \frac{2P_{Smax}-2C_A-C_{max}}{4}$
  - In this case if $P_{Smax} \geq P_A^* + C_D$ or $P_{Smax} - C_A \geq \frac{4C_D-C_{max}}{2} \rightsquigarrow P_D^* = \frac{P_{Smax}-P_A^*+C_D}{2} = \frac{2P_{Smax}-2C_A+4C_D+C_{max}}{8} \rightsquigarrow pi_D(P_D^*) = \frac{2P_{Smax}-2C_A-4C_D+C_{max}}{8}$

In Table 4.5 we show the profits of A and D (i.e., $P_i^* - C_i$, where $i = A, D$) that result from those optimal points. Allow $M = P_{Smax} - C_A$. Note that when $P_{Smax} - C_A < \frac{3C_D}{2}$ the service is not offered, because D cannot make any profits. However, this is a condition that A cannot validate and avoid. In Fig. **??** we show the profits of A and D for different values of P_{Smax}/C_{max}. In the first case,

P_S is uniformly distributed in the interval [0, C_{max}], in the second in [0, 1.5C_{max}] in the third in [0, 2C_{max}] and the last one in [0, 3C_{max}]. For each such case, we select 100 random pairs of C_A and C_D from the uniform distribution in [0, 1]. For the percentages and ratios of profits of A and D we ran the numerical analysis of the model for 1000 pairs of C_A and C_D and we calculated the mean values. The cross spots indicate the cases where the service is not offered due to the violation of the constraint $C_D + P_A \leq P_{Smax}$ and hence because D's cost exceeds the maximum price that it believes that is left for it. The relevant percentages are 2.2%, 3%, 1.1% and 0% in the corresponding cases. The star spots represent the cases where the service cannot be offered because the sum of the prices of the two NSPs is higher than the price of the buyer. In the four cases this is happening for 1.9%, 4.7%, 7.9% and 21.2% of the times respectively. The percentages are increasing since the interval of the uniform distribution that we use to extract the random value of P_S is increasing along with P_{Smax}. Also there is the case where the sum of the costs of the two NSPs is higher than the value of the buyer, and the service cannot inherently be offered. The relevant percentages are 82.9%, 65.5%, 50.5%, 32.4% respectively, shown by point spots. Last, the service is given for 13%, 26.7%, 40.5% and 46.4% of the times respectively in each of the four cases (triangle spots). Also as seen in the figure the triangle spots that correspond to a given service are always under the line x=y. This means that A always has a larger profit than D, on the average by 3.33, 4.53, 3.91 and 2.20 times respectively. Thus, while A maintains an advantage over D as in the Distributed Pull model, this advantage is now lower. Moreover, as in the Distributed Pull model, the selfish behaviour of A may cause the failure of the provision of the service due to unwillingness of D to participate. But in this model, another failure can occur due to erroneous expectations of the NSPs for the buyer's price, which is not precisely known. Hence, we can expect that the Distributed Push model has lower probability of offering the service, as we show in the next Subsection. However, although by being first in the chain NSP A still has an advantage over D, its selfish behaviour is suppressed due to the uncertainty on the buyer's price.

Analysis of Efficiency. We can further evaluate this model by estimating the loss in efficiency, by comparing the difference between the probability that the

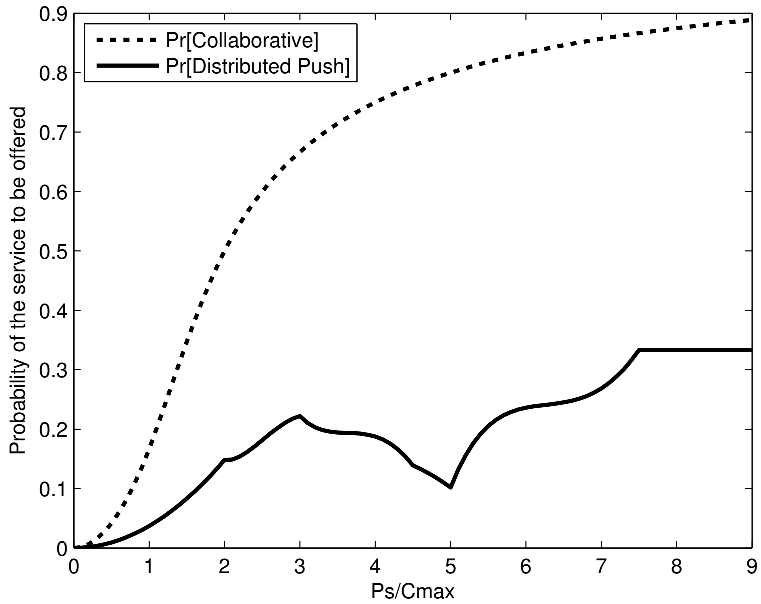

Figure 4.18: Comparison of Pr[service] in the Collaborative and the Distributed Push Model

service is indeed offered under the Distributed Push model Pr$[P_D + P_A \leq P_S]$ and that under the Collaborative model Pr$[C_D + C_A \leq P_S]$. For a given value of P_S, the conditional probability Pr[service$|P_S$] of the Collaborative model is obtained from a triangle distribution with support in [0,2C_{max}], as already shown in previous sections and Appendix B. Thus, we have: Pr[service] = E[Pr$[C_D + C_A \leq P_S|P_S]$] = E$[Pr[Z < P_S|P_S]]$, or else:

$$\int_0^{P_{Smax}} F_Z(p) f_{P_S}(p) dp,$$

where Z is a random variable following the aforementioned triangle distribution. Since P_S follows a uniform distribution U $\sim [0, P_{Smax}]$ the pdf of P_S is $f_{P_S} = \frac{1}{P_{Smax}}$. Thus, depending on the relation between C_{max} and P_{Smax} we distinguish three different cases for Pr$[C_D + C_A \leq P_S]$. The cases are analysed in Appendix G.

For the Distributed Push model case we calculate the following probability: Pr[service]=Pr$[P_A^* + P_D^* \leq P_S]$ = Pr$[\frac{2C_A + 4P_{Smax} + 3C_D}{6} \leq P_S]$ =Pr$[2C_A + 3C_D \leq 6P_S - 4P_{Smax}]$. Since C_A and C_D are independent and identically, uniformly distributed, employing convolution, we obtain after some algebra the cumulative distribution function F_R of the random variable $R = 2C_A + 3C_D$. Note that $F_R(r)$ is given by a different expression for r in $[0,\ 2C_{max})$, $[2C_{max},\ 3C_{max})$, $[3C_{max},\ 5C_{max})$, while equals 1 for $r > 5C_{max}$. Furthermore, using F_R, we proceed as follows: $\Pr[\text{service}|P_S = p] = \Pr[R \leq 6P_S - 4P_{Smax}|P_S = p]$. Note that: $6P_S - 4P_{Smax} \geq 0 \leftrightarrow P_S \geq \frac{2P_{Smax}}{3}$. Thus, $\Pr[\text{service}|P_S = p]$ does not vanish only if p takes values in the interval $[\frac{2P_{Smax}}{3}, P_{Smax}]$. This readily implies that $\Pr[\text{service}] \leq 1/3$, since P_S is uniformly distributed. Thus, the probability that service is indeed offered under the Distributed Push model is low. The exact calculation of this probability is rather tedious, since it depends on the relation between P_{Smax} and C_{max}. Using the cdf, we calculate the probability of the service being offered. The fact that there are six cases due to the constraint $p \geq \frac{2P_{Smax}}{3}$ and the form of the cdf, yields a function of P_{Smax}/C_{max} that is continuous but not differentiable everywhere. $\Pr[\text{service}|P_S = p]$ can also be written as:

$$\int_0^{P_{Smax}} F_R(p) f_{P_S}(p) dp,$$

where R is a random variable following the aforementioned distribution. Since P_S follows a uniform distribution U $\sim [0, P_{Smax}]$ the pdf of P_S is $f_{P_S} = \frac{1}{P_{Smax}}$. The six cases formed are presented in Appendix G. In Fig. 4.18, we depict the probability of service indeed offered for the Collaborative model (dotted line) and the same probability of the Distributed Push model (solid line). Surprisingly, the latter is not a monotonic function of P_{Smax}/C_{max}. Their highest difference is when P_S is close to $5C_{max}$. In general, we notice a high loss of efficiency for the Push model, compared to the Collaborative one, due to the selfish behaviour of NSP A, and the uncertainties involved.

4.6 Conclusions

In the previous sections we studied two main distributed coordination models, the Pull and the Push ones for the creation of end-to-end paths over which services based on QoS assurances can be provided. The main difference between these models concerns the available information to the NSPs. For tractability reasons we analysed the case of the three interconnected providers, which (among others) models the interactions among an InfP, a transit NSP and an access NSP. This simple case is common in reality. In both models the provider immediately after the buyer in the chain is more profitable, since it chooses its prices first and thus squeezes the profit of the other provider. In general, it is reasonably expected that this property extends to the case of a service served in a longer end-to-end path. In such a case, the providers closer to the buyer would have an advantage compared to the others. In the Pull model the providers' prices are not pre-decided and thus they are chosen in accordance to the offer of the buyer of the service. On the other hand, in the Push model this type of behaviour does not apply, since the offers are prepared without any knowledge about the price of a specific buyer and this is why the first provider in the chain gains less than in the previous model. However, comparing the probabilities of the service being offered in both cases, it follows that the Pull model is more efficient than the Push one. This discrepancy results from the set of the available information in the two models. In particular, in the Push model, there is a considerably larger possibility for the buyer's price to be small enough so that the service is not given. The Push model is still less efficient even if the buyer in the Pull model shades his price, as shown in Fig. 4.19.

New cloud service providers appeared in the past few years and the traffic that results from such services is growing. More and more companies and individuals adopt the new less costly services provided on the cloud. Video streaming and on-line gaming, which are provided in similar manners too, also compete for a large portion of Internet traffic. In the next few years the emergence of end-to-end quality assurances will be necessary. In such a less mature market, where the demand is unpredictable and not high, a Pull model is more preferable. The providers may process individually each of the few requests, learning also the buyers' offered prices for such services, and provide tailored offers. In a topology where all providers have end-users for such services, the highly advantageous position that the first provider may obtain under this model in each specific case, may be balanced on the average if it covers many source-destination pairs. In a large and mature market, a Push model is better, assuming that the buyers' willingness to pay is more predictable than in our study. In fact, in our formula-

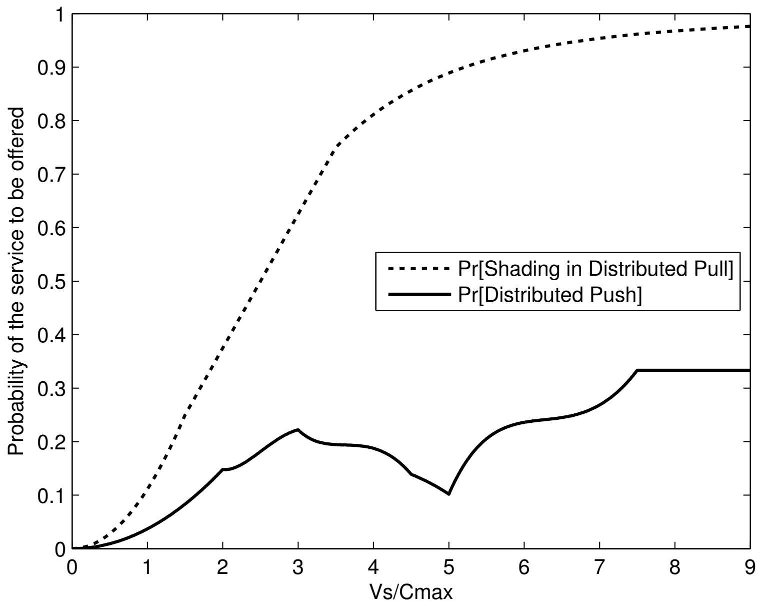

Figure 4.19: Comparison of Pr[service] in the Shading Distributed Pull and the Distributed Push Model

tion we used a uniform distribution for the price of the buyer indicating a high degree of unpredictability that does not pertain to a mature market. Under this model the discrepancy between the prices of the providers is much less. However, both models show that the selfishness of the players involved has a considerable detrimental effect on the end user satisfaction, since our results showed that the probability that the service is offered when the first provider acts selfishly is considerably lower than that in the respective ideal collaborative model.

Chapter 5

Conclusions

Here I put my conclusions ...

Appendix A

Optimal Prices and Expected Benefits in Distributed Pull Model with Unknown Costs

Optimal (actual) prices for A.

Case 1: Beginning with Case 1, we formulate the Lagrangian function as follows:

$$\mathrm{L} = (P_A - C_A)\frac{P_S - P_A}{C_{max}} + \lambda_1(P_S - P_A) + \lambda_2(P_A - C_A)$$

$$\frac{\partial L}{\partial P_A} = \frac{P_S - 2P_A + C_A}{C_{max}} - \lambda_1 + \lambda_2$$

s.t. $P_S - P_A \geq 0$, $P_A - C_A \geq 0$, $\lambda_1, \lambda_2 \geq 0$.

According to the constraints, we have:
$\lambda_1(P_S - P_A) = 0$, which gives as two possible solutions, i.e., $\lambda_1 = 0$ or $P_S = P_A$ and
$\lambda_2(P_A - C_A) = 0$, which gives as two possible solutions, i.e., $\lambda_2 = 0$ or $P_A = C_A$

Combining the possible solutions we obtain four different cases:

First: $\lambda_1 = \lambda_2 = 0$

In this case solving $\frac{\partial L}{\partial P_A} = 0$, we obtain $P_A = \frac{P_S + C_A}{2}$. Since the second derivative is negative in the entire interval, we have a maximum at the point where the first derivative vanishes. $P_A = \frac{P_S + C_A}{2}$ belongs to $[C_A \; P_S]$, since $C_A \leq \frac{P_S + C_A}{2}$ and $\frac{P_S + C_A}{2} \leq P_S$. Thus, since this point belongs to the feasible region and the first derivative vanishes, it is a maximum point.

Second: $\lambda_1 = 0$, $P_A = C_A$

In this case, if we substitute $P_A = C_A$ to 4.2 we result in $(P_A - C_A)\frac{P_S - P_A}{C_{max}} = 0$. Thus, this is a minimum point.

Third: $\lambda_2 = 0$, $P_S = P_A$

Again, this point corresponds to a minimum since $(P_A - C_A)\frac{P_S - P_A}{C_{max}} = 0$.

Fourth: $P_A = C_A$, $P_S = P_A$

This case can only apply if by coincidence $P_S = C_A$. But even then A does not have any option in choosing P_A, except for $P_A = C_A$, which is the same as in second case.

Thus we have one possible maximum point for Case 1 (4.2) and that is $P_A = \frac{P_S + C_A}{2}$.

Case 2: Continuing with Case 2 (4.3), we formulate the Lagrangian function accordingly:

$$\mathrm{L} = (P_A - C_A)\frac{P_S - P_A}{C_{max}} + \lambda_1(P_S - P_A) + \lambda_2(P_A + C_{max} - P_S)$$

$$\frac{\partial L}{\partial P_A} = \frac{P_S - 2P_A + C_A}{C_{max}} - \lambda_1 + \lambda_2$$

s.t. $P_S - P_A \geq 0$, $P_A + C_{max} - P_S \geq 0$, $\lambda_1, \lambda_2 \geq 0$.

According to the constraints, we have:
$\lambda_1(P_S - P_A) = 0$, which gives as two possible solutions, i.e., $\lambda_1 = 0$ or $P_S = P_A$ and
$\lambda_2(P_A + C_{max} - P_S) = 0$, which gives as two possible solutions, i.e., $\lambda_2 = 0$ or $P_A = P_S - C_{max}$

Combining the possible solutions we obtain four different cases:

First: $\lambda_1 = \lambda_2 = 0$
In this case solving $\frac{\partial L}{\partial P_A} = 0$, we obtain $P_A = \frac{P_S + C_A}{2}$. Since the second derivative is negative in the entire interval, we have a maximum at the point where the first derivative vanishes. $P_A = \frac{P_S+C_A}{2}$ belongs to $[C_A\ P_S]$, since $C_A \leq \frac{P_S+C_A}{2}$ and $\frac{P_S+C_A}{2} \leq P_S$. If $\frac{P_S+C_A}{2} \geq P_S - C_{max}$, then $\frac{P_S+C_A}{2}$ is the maximum point, otherwise $P_S - C_{max}$ is the maximum point, since the function is increasing in the interval $[C_A\ P_S]$.

Second: $\lambda_1 = 0$**,** $P_A = P_S - C_{max}$
This point corresponds to a maximum if $\frac{P_S+C_A}{2}$ point does not belong to the $[P_S - C_{max}\ P_S]$, since the function is decreasing in this interval.

Third: $\lambda_2 = 0$**,** $P_S = P_A$
This point corresponds to a minimum since $(P_A - C_A)\frac{P_S - P_A}{C_{max}} = 0$.

Fourth: $P_A = C_A$**,** $P_A = P_S - C_{max}$
This case is not feasible.

Thus we have two possible maximum points for Case 2 (4.3) and those are $P_A = \frac{P_S+C_A}{2}$ and $P_A = P_S - C_{max}$. Summarizing both cases, we have:

- If $0 \leq P_S \leq C_{max} + C_A$, then the maximum point is $P_A = \frac{P_S+C_A}{2}$.
- If $C_A + C_{max} \leq P_S \leq 2C_{max} + C_A$, then the maximum point is again $P_A = \frac{P_S+C_A}{2}$.
- If $P_S \geq 2C_{max} + C_A$, then the maximum point is $P_A = P_S - C_{max}$. This case definitely applies for $P_S \geq 3C_{max}$.

Case 3: This case is only meaningful when $P_S \geq C_{max}$. The upper bound of the integral is now C_{max}. This alters the expression that A maximizes into:

$$\max_{P_A}(P_A - C_A) \int_{C_D=0}^{C_{max}} \frac{dC_D}{C_{max}}.$$

Solving the integral, we have $max_{P_A}(P_A - C_A)$ (4.4), which stand for the expected benefits of A. Since this is a linear function with a positive slope it is maximized at the upper bound for P_A, which is $P_A = P_S - C_{max}$. Thus for Case 3 the maximum is attained for $P_A = P_S - C_{max}$. This either coincides with a maximum point, or with a point that has been already found to be sub-optimal.

Expected benefits for A and D. Given this optimal choice and the value C_A, we can compute the probability that the service is actually offered, which equals the probability $Pr[C_D \leq P_S - P_A]$. We replace P_A with the optimal points and we compute the probability that the service is indeed offered at these points. If $P_S \in [0\ 2C_{max} + C_A]$ then

- $Pr[C_D \leq P_S - P_A^*] = Pr[C_D \leq \frac{P_S - C_A}{2}] = \int_0^{\frac{P_S - C_A}{2}} \frac{1}{C_{max}} dC_D = \frac{P_S - C_A}{2C_{max}}$

If $P_S \in (2C_{max} + C_A,\ \infty)$ then,

- $Pr[C_D \leq P_S - P_A^*] = Pr[C_D \leq C_{max} = \int_0^{C_{max}} \frac{1}{C_{max}} dC_D = 1$

This also can be considered as the estimate of A for this probability, since he knows the values of both P_S and C_A. Further we calculate the expected benefit for A given his value C_A at the maximization point. Replacing P_A with its values at these points we obtain: If $P_S \in [0\ 2C_{max} + C_A]$ then

- $G_{C_A}(C_A) = \frac{P_S - C_A}{2} \frac{P_S - C_A}{2C_{max}} = \frac{(P_S - C_A)^2}{4C_{max}}$, for A and
- $G_{C_A,C_D}(C_A, C_D) = P_D - C_D = P_S - P_A^* - C_D = P_S - \frac{P_S + C_A}{2} - C_D = P_S - C_A - 2C_D$, for D

If $P_S \in (2C_A + C_{max},\ \infty)$ then,

- $G_{C_A}(C_A) = \frac{P_S - C_A}{2}$, for A and
- $G_{C_A,C_D}(C_A, C_D) = P_D - C_D = P_S - P_A - C_D = C_{max} - C_D$

Appendix B

Calculation of Probability[Service] for the Collaborative Pull Scenario

In order to calculate the probability of Pr[service]= $\Pr[C_A + C_D \leq P_S]$ we find the joint distribution function of C_A and C_D. Since the two variables are independent and uniformly distributed in the interval $[0\ C_{max}]$, the joint distribution function is:

$$f_{C_A C_D}(C_A, C_D) = f_{C_A}(C_A) f_{C_D}(C_D) = \frac{1}{C_{max}^2}.$$

Thus, taking into consideration the bounds of the variables, we have:

$$f_{C_A C_D}(C_A, C_D) = \begin{cases} \frac{1}{C_{max}^2} & \text{if } 0 \leq C_A,\ C_D \leq C_{max} \\ 0 & \text{otherwise} \end{cases}$$

This means that the joint pdf takes the value $\frac{1}{C_{max}^2}$ inside the square that is defined by the bounds and 0 everywhere else. We can now calculate the distribution of $C_A + C_D \leq Z$ along which integration takes place, help us to distinguish three different cases:

Case 1 - $(0 > z)$, $(z \geq 2C_{max})$: In this case the line does not intersect with the square. Thus $f_Z(z) = 0$.

Case 2 - $(0 \leq z < C_{max})$**:** In this case the line intersects with the x-axis at $x = z$ and

$$f_Z(z) = \int_{C_A=0}^{z} \frac{1}{C_{max}^2} dC_A = \frac{z}{C_{max}^2}.$$

Case 3 - $C_{max} \leq z < 2C_{max}$**:** The line intersects the square for $z - C_{max} \leq C_A \leq C_{max}$ and

$$f_Z(z) = \int_{C_A=z-C_{max}}^{C_{max}} \frac{1}{C_{max}^2} dC_A = \frac{2C_{max} - z}{C_{max}^2}.$$

Combining the three cases and the corresponding bounds, we have:

$$f_Z(z) = \begin{cases} \frac{z}{C_{max}^2} & \text{if } 0 \leq z \leq C_{max} \\ \frac{2C_{max}-z}{C_{max}^2} & \text{if } C_{max} \leq z \leq 2C_{max} \\ 0 & \text{otherwise} \end{cases}$$

$f_Z(z)$ is a triangular distribution, of which we calculate the cumulative distribution function:

$$F_Z(z) = \begin{cases} 0 & \text{if } a < 0 \\ \frac{a^2}{2C_{max}^2} & \text{if } 0 \leq a < C_{max} \\ \frac{2a}{C_{max}} - \frac{a^2}{2C_{max}^2} - 1 & \text{if } C_{max} \leq a < 2C_{max} \\ 1 & \text{if } 2C_{max} \leq a \end{cases}$$

At this point we can calculate the probability of a service to be offered, when the NSPs collaborate with each other.

Appendix C

Calculation of Probability[Service] for the Distributed Pull Scenario

In order to calculate the Pr[service]=Pr[$2C_D + C_A \leq P_S$] we follow the next steps. We calculate first the joint distribution of $2C_D + C_A$. Let $2C_D = R$. Then R is obviously distributed in the interval $[0,\ 2C_{max}]$. Thus we have the distribution of R, which is $f_R(a) = \frac{1}{2C_{max}}$. We now calculate the joint distribution function of $2C_D$ and C_A.

$$f_{RC_A}(w, C_A) = f_R(r) f_{C_A}(C_A) = \begin{cases} \frac{1}{C_{max}^2} & \text{if } 0 \leq C_A < C_{max} \\ 0 & \text{otherwise} \end{cases}$$

Then we will calculate the probability density function of $R + C_A$. In this case the support of the distribution of the pair $(R,\ C_A)$ is a rectangle, which is defined by the points $(0,\ 0)$, $(0,\ C_{max})$, $(2C_{max},\ 0)$, $(2C_{max},\ C_{max})$. The density is positive only in this rectangle, and we distinguish four different cases:

Case 1 - $(0 > w)$**,** $(z \geq 3C_{max})$**:** In this case the line does not intersect with the rectangle. Thus $f_W(w) = 0$.

Case 2 - $(0 \leq w < C_{max})$**:**

$$f_W(w) = \int_{r=0}^{w} \frac{1}{2C_{max}^2} dr = \frac{w}{2C_{max}^2}.$$

Case 3 - $C_{max} \leq w < 2C_{max}$**:**

$$f_W(w) = \int_{r=w-C_{max}}^{w} \frac{1}{2C_{max}^2} dr = \frac{C_{max}}{2C_{max}^2} = \frac{1}{2C_{max}}.$$

Case 4 - $2C_{max} \leq w < 3C_{max}$**:**

$$f_W(w) = \int_{r=w-C_{max}}^{2C_{max}} \frac{1}{2C_{max}^2} dr = \frac{3C_{max} - w}{2C_{max}^2}.$$

Concluding to a probability density function:

$$f_W(w) = \begin{cases} \frac{w}{2C_{max}^2} & \text{if } 0 \leq w \leq C_{max} \\ \frac{C_{max}}{2C_{max}^2} & \text{if } C_{max} \leq w \leq 2C_{max} \\ \frac{3C_{max}-w}{2C_{max}^2} & \text{if } 2C_{max} \leq w \leq 3C_{max} \\ 0 & \text{otherwise} \end{cases}$$

We calculate the cumulative distribution function of $f_W(w)$, which is:

$$F_W(w) = \begin{cases} 0 & \text{if } a < 0 \\ \frac{a^2}{4C_{max}^2} & \text{if } 0 \leq a < C_{max} \\ \frac{a}{2C_{max}} - \frac{1}{4} & \text{if } C_{max} \leq a < 2C_{max} \\ \frac{-5C_{max}^2+6aC_{max}-a^2}{4C_{max}^2} & \text{if } 2C_{max} \leq a < 3C_{max} \\ 1 & \text{if } 3C_{max} \leq a \end{cases}$$

Appendix D

Optimal Bids for Distributed Pull Models for Shading Bid

Shading Bid for Collaborative Model We proceed by solving the maximization problems. For Case 1 we create the Lagrangian equation.

$$\mathrm{L} = (V_S - P_S)\frac{P_S^2}{2C_{max}^2} + \lambda_1(V_S - P_S)$$

s.t. $V_S - P_S \geq 0$

$$\frac{\partial L}{\partial P_S} = \frac{2P_S V_S}{2C_{max}^2} - \frac{3P_S^2}{2C_{max}^2} - \lambda_1$$

s.t. $V_S - P_S \geq 0$, $\lambda_1 \geq 0$.

According to the constraints, we have:
$\lambda_1(V_S - P_S) = 0$, which gives as two possible solutions, i.e., $\lambda_1 = 0$ or $V_S = P_S$. For $\lambda_1 = 0$, $\frac{\partial L}{\partial P_S} = 0$ and thus:

$$\frac{2P_S V_S}{2C_{max}^2} - \frac{3P_S^2}{2C_{max}^2} = 0 \Leftrightarrow 2P_S V_S - 3P_S^2 = 0 \Leftrightarrow P_S(2V_S - 3P_S) = 0$$

Thus $P_S = 0$ or $P_S = \frac{2V_S}{3}$. For that optimal point the profits of the buyer equal

$$\pi_S = (V_S - P_S)\frac{P_S^2}{2C_{max}^2} = \frac{2V_S^3}{27C_{max}^2}$$

For Case 2, we form the Lagrangian equation for the maximization problem 4.9.

$$\mathrm{L} = (V_S - P_S)(\frac{2P_S}{C_{max}} - \frac{P_S^2}{2C_{max}^2} - 1) + \lambda_1(V_S - P_S) + \lambda_2(P_S - C_{max}) + \lambda_3(2C_{max} - P_S)$$

s.t. $V_S - P_S \geq 0$, $P_S - C_{max} \geq 0$, $2C_{max} - P_S > 0$.

$$\frac{\partial L}{\partial P_S} = \frac{2V_S}{C_{max}} - \frac{2P_S V_S}{2C_{max}^2} - \frac{4P_S}{C_{max}} + \frac{3P_S^2}{2C_{max}^2} + 1 - \lambda_1 + \lambda_2 - \lambda_3$$

s.t. $V_S - P_S \geq 0$, $P_S - C_{max} \geq 0$, $2C_{max} - P_S > 0$.

According to the constraints, we have:
$\lambda_1(V_S - P_S) = 0$, $\lambda_2(P_S - C_{max})$, $\lambda_3(2C_{max} - P_S)$ which gives as eight possible solutions.

Case 1 - $\lambda_1 = 0,\ P_S = C_{max},\ \lambda_3 = 0$**:** Substituting in 4.9 we have:

$$(V_S - P_S)(\frac{2P_S}{C_{max}} - \frac{P_S^2}{2C_{max}^2} - 1) = \frac{V_S - C_{max}}{2}$$

Case 2,3 - $\lambda_1 = 0,\ P_S = C_{max},\ P_S = 2C_{max}$ **and** $V_S = P_S$**,**$P_S = C_{max}$**,**$P_S = 2C_{max}$ **:** Not possible.

Case 4 - $\lambda_1 = 0,\ \lambda_2 = 0,\ P_S = 2C_{max}$**:**

$$(V_S - P_S)(\frac{2P_S}{C_{max}} - \frac{P_S^2}{2C_{max}^2} - 1) = V_S - 2C_{max}$$

Case 5, 6, 7 - $V_S = P_S$**,** $\lambda_2 = 0$**,** $\lambda_3 = 0$ **or** $V_S = P_S$**,** $P_S = C_{max}$**,** $\lambda_3 = 0$ **and** $V_S =$

P_S, $\lambda_2 = 0$, $P_S = 2C_{max}$: In all these cases:

$$(V_S - P_S)(\frac{2P_S}{C_{max}} - \frac{P_S^2}{2C_{max}^2} - 1) = 0$$

Case 8, - $\lambda_1 = 0$, $\lambda_2 = 0$, $\lambda_3 = 0$: Since $\frac{\partial L}{\partial P_S} = 0$, substituting we have:

$$\frac{2V_S}{C_{max}} - \frac{2P_S V_S}{2C_{max}^2} - \frac{4P_S}{C_{max}} + \frac{3P_S^2}{2C_{max}^2} + 1 = 0 \Leftrightarrow$$

$$\frac{4V_S C_{max} - 2P_S V_S - 8P_S C_{max} = 3P_S^2 + 2C_{max}^2}{2C_{max}^2} = 0 \Leftrightarrow$$

$$4V_S C_{max} - 2P_S V_S - 8P_S C_{max} = 3P_S^2 + 2C_{max}^2 = 0 \Leftrightarrow$$

$$P_S = \frac{-(-2V_S - 8C_{max}) \pm \sqrt{(-2V_S - 8C_{max})^2 - 12(4V_S C_{max} + 2C_{max}^2)}}{6} \Leftrightarrow$$

$$P_S = \frac{2V_S + 8C_{max}) \pm \sqrt{(4V_S^2 + 32V_S C_{max} + 64C_{max}^2 - 48V_S C_{max} - 24C_{max}^2}}{6} \Leftrightarrow$$

$$P_S = \frac{2V_S + 8C_{max}) \pm \sqrt{(4V_S^2 - 16V_S C_{max} + 40C_{max}^2}}{6}$$

For Case 3, we form the Lagrangian equation for the maximization problem 4.10.

$$\text{L} = (V_S - P_S) + \lambda_1(V_S - P_S) + \lambda_2(P_S - C_{max})$$

s.t. $V_S - P_S \geq 0$, $P_S - 2C_{max} \geq 0$.

$$\frac{\partial L}{\partial P_S} = -1 - \lambda_1 + \lambda_2 = 0$$

s.t. $V_S - P_S \geq 0$, $P_S - 2C_{max} \geq 0$, λ_1, $\lambda_2 \geq 0$.

For $\lambda_1 = 0$, $\lambda_2 = 0$: Is not possible. For $\lambda_1 = 0$, $P_S = 2C_{max}$: Equation 4.8 equals $V_S - 2C_{max}$ For $P_S = V_S$, $\lambda_2 = 0$ or $P_S = V_S$, $P_S = 2C_{max}$: equation 4.10 equals 0.

Shading Bid for Distributed Model

Case 1 - $0 \leq P_S < C_{max}$**:**

$$\max_{P_S}(V_S - P_S)\frac{P_S^2}{4C_{max}^2} \tag{D.1}$$

$$\mathrm{L} = (V_S - P_S)\frac{P_S^2}{4C_{max}^2} + \lambda_1(V_S - P_S) + \lambda_2(C_{max} - P_S)$$

s.t. $V_S - P_S \geq 0$, $C_{max} - P_S \geq 0$.

$$\frac{\partial L}{\partial P_S} = \frac{2P_SV_S}{4C_{max}^2} - \frac{3P_S^2}{4C_{max}^2} - \lambda_1 - \lambda_2$$

s.t. $V_S - P_S \geq 0$, $C_{max} - P_S \geq 0$, λ_1, $\lambda_2 \geq 0$ Thus we may have $\lambda_1 = 0$, $\lambda_2 = 0$, $V_S = P_S$, $C_{max} = P_S$. For all those combinations we have:

Case i - $\lambda_1 = \lambda_2 = 0$**:** If this is the case then

$$\frac{2P_SV_S}{4C_{max}^2} - \frac{3P_S^2}{4C_{max}^2} = 0 \Leftrightarrow$$

$$P_S(2V_S - 3P_S = 0 \Leftrightarrow P_S = 0 \text{ or } P_S = \frac{2V_S}{3}$$

For $P_S = 0$ then D.1 equals 0. For $P_S = \frac{2V_S}{3}$, then D.1 equals:

$$(V_S - P_S)\frac{P_S^2}{4C_{max}^2} = (V_S - \frac{2V_S}{3})\frac{4V_S^2}{36C_{max}^2} = \frac{V_S^3}{27C_{max}^2}$$

Case ii - $V_S = P_S$**,** $\lambda_2 = 0$**:** In this case D.1 equals 0 and thus this is a minimum.

Case iii - $\lambda_1 = 0$**,**$C_{max} = P_S$**:** In this case the equation D.1 equals $\frac{V_S - C_{max}}{4}$.

Case iv - $P_S = V_S = C_{max}$**:** In this case again D.1 equals 0.

Case 2 - $C_{max} \leq P_S < 2C_{max}$**:** Then our maximization problem becomes:

$$\max_{P_S}(V_S - P_S)(\frac{P_S}{2C_{max}} - \frac{1}{4}) \tag{D.2}$$

And the Lagrangian becomes:

$$L = (V_S - P_S)(\frac{P_S}{2C_{max}} - \frac{1}{4}) + \lambda_1(V_S - P_S) + \lambda_2(P_S - C_{max}) + \lambda_3(2C_{max} - P_S)$$

s.t. $V_S - P_S \geq 0$, $2C_{max} - P_S \geq 0$, $P_S - C_{max} \geq 0$, $\lambda_1,\ \lambda_2,\ \lambda_3 \geq 0$

$$\frac{\partial L}{\partial P_S} = \frac{V_S}{2C_{max}} - \frac{2P_S}{2C_{max}} + \frac{1}{4} - \lambda_1 + \lambda_2 - \lambda_3$$

s.t. $V_S - P_S \geq 0$, $2C_{max} - P_S \geq 0$, $P_S - C_{max} geq 0$, $\lambda_1,\ \lambda_2,\ \lambda_3 \geq 0$. Thus we may have $\lambda_1 = 0$, $\lambda_2 = 0$, $\lambda_3 = 0$, $V_S = P_S$, $C_{max} = P_S$, $P_S = 2C_{max}$ For all those combinations we have:

Case i - $\lambda_1 = \lambda_2 = \lambda_3 = 0$: In such case D.2= 0 becomes:

$$(V_S - P_S)(\frac{P_S}{2C_{max}} - \frac{1}{4}) = 0 \Leftrightarrow$$

$$\frac{2V_S - 4P_S + 2C_{max}}{4C_{max}} = 0 \Leftrightarrow$$

$$P_S = \frac{2V_S + C_{max}}{4}$$

Also the expected profit that the buyer has because of shading his bid becomes from D.2:

$$(V_S - \frac{2V_S + C_{max}}{4})(\frac{2V_S + C_{max}}{4C_{max}} - \frac{1}{4}) = \frac{V_S^2}{8C_{max}} - \frac{V_S}{8} + \frac{C_{max}}{32}$$

Case ii - $\lambda_1 = \lambda_3 = 0$, $C_{max} = P_S$: In this case the expected profit of the buyer (D.2) becomes:

$$(V_S - C_{max})(\frac{C_{max}}{2C_{max}} - \frac{1}{4}) = \frac{V_S - C_{max}}{4}$$

Case iii - $\lambda_1 = \lambda_3 = 0$, $P_S = 2C_{max}$: In this case the expected profit of the buyer (D.2) becomes:

$$(V_S - 2C_{max})(\frac{2C_{max}}{2C_{max}} - \frac{1}{4}) = \frac{3(V_S - 2C_{max})}{4}$$

Cases iv, v - $P_S = V_S = C_{max} = 2C_{max}$**, or** $P_S = C_{max} = 2C_{max}$**,** $\lambda_1 = 0$**:** This is not possible in both cases.

Case vi, vii, viii - $P_S = V_S$**,**$\lambda_1 = \lambda_3 = 0$ **or** $P_S = V_S = C_{max}$**,** $\lambda_3 = 0$ **or** $P_S = V_S = 2C_{max}$, $\lambda_2 = 0$: In all those cases D.2 equals zero and thus those points are minimums.

Case 3 - $2C_{max} \leq P_S < 3C_{max}$**:** Then our maximization problem becomes:

$$\max_{P_S}(V_S - P_S)\frac{-5C_{max}^2 + 6P_SC_{max} - P_S^2}{4C_{max}^2} \tag{D.3}$$

And the Lagrangian becomes:

$$\text{L} = (V_S - P_S)\frac{-5C_{max}^2 + 6P_SC_{max} - P_S^2}{4C_{max}^2} + \lambda_1(V_S - P_S) + \lambda_2(P_S - 2C_{max}) + \lambda_3(3C_{max} - P_S)$$

s.t. $V_S - P_S \geq 0$, $P_S - 2C_{max} \geq 0$, $3C_{max} - P_S \geq 0$, $\lambda_1,\ \lambda_2,\ \lambda_3 \geq 0$

$$\frac{\partial L}{\partial P_S} = \frac{6C_{max}V_S - 2P_SV_S + 5C_{max}^2 - 12P_SC_{max} + 3P_S^2}{4C_{max}^2} - \lambda_1 + \lambda_2 - \lambda_3 \tag{D.4}$$

s.t. $V_S - P_S \geq 0$, $P_S - 2C_{max} \geq 0$, $3C_{max} - P_S \geq 0$, $\lambda_1,\ \lambda_2,\ \lambda_3 \geq 0$. Thus we may have $\lambda_1 = 0$, $\lambda_2 = 0$, $\lambda_3 = 0$, $V_S = P_S$, $2C_{max} = P_S$, $P_S = 3C_{max}$ For all those combinations we have:

Case i - $\lambda_1 = \lambda_2 = \lambda_3 = 0$**:** Then from D.4 we have:

$$\frac{6C_{max}V_S - 2P_SV_S + 5C_{max}^2 - 12P_SC_{max} + 3P_S^2}{4C_{max}^2} = 0 \Leftrightarrow$$

$$6C_{max}V_S - 2P_SV_S + 5C_{max}^2 - 12P_SC_{max} + 3P_S^2 = 0 \Leftrightarrow$$

$$P_S = \frac{-(2V_S - 12C_{max}) \pm \sqrt{(-2V_S - 12C_{max})^2 - 12(6C_{max}V_S + 5C_{max}^2)}}{6} \Leftrightarrow$$

$$P_S = \frac{2V_S + 12C_{max} \pm \sqrt{4V_S^2 - 24C_{max}V_S + 84C_{max}^2}}{6}$$

Case ii - $\lambda_1 = \lambda_3 = 0$, $2C_{max} = P_S$: In this case D.3 becomes:

$$\max_{P_S}(V_S - 2C_{max})\frac{-5C_{max}^2 + 12C_{max}^2 - 4C_{max}^2}{4} = \frac{3(V_S - 2C_{max})}{4}$$

Case iii - $\lambda_1 = \lambda_2 = 0$, $3C_{max} = P_S$: In this case D.3 becomes:

$$\max_{P_S}(V_S - 3C_{max})\frac{-5C_{max}^2 + 18C_{max}^2 - 9C_{max}^2}{4} = (V_S - 3C_{max})\frac{4C_{max}^2}{4C_{max}^2} = V_S - 3C_{max}$$

Cases iv, v - $P_S = V_S = 2C_{max} = 3C_{max}$ or $P_S = 2C_{max} = 3C_{max}$, $\lambda_1 = 0$: These cases are not possible.

Cases vi, vii, vii - $P_S = V_S$, $\lambda_3 = \lambda_2 = 0$ or $P_S = V_S = 2C_{max}$, $\lambda_3 = 0$ or $P_S = V_S = 3C_{max}$, $\lambda_2 = 0$: In all these cases D.3 equals zero.

Case 4 - $3C_{max} \leq P_S$ In this case

$$\max_{P_S}(V_S - P_S)\Pr[C_A + 2C_D \leq P_S] = (V_S - P_S) \cdot 1 \qquad \text{(D.5)}$$

s.t. $V_S - P_S \geq 0$, $P_S - 3C_{max} \geq 0$ And the Lagrangian becomes:

$$\mathrm{L} = (V_S - P_S) + \lambda_1(V_S - P_S) + \lambda_2(P_S - 3C_{max})$$

s.t. $V_S - P_S \geq 0$, $P_S - 3C_{max} \geq 0$ λ_1, $\lambda_2 \geq 0$

$$\frac{\partial L}{\partial P_S} = -1 - \lambda_1 + \lambda_2$$

s.t. $V_S - P_S \geq 0$, $P_S - 3C_{max} \geq 0$ λ_1, $\lambda_2 \geq 0$ Again due to the combinations we have:

Case i - $\lambda_1 = \lambda_2 = 0$ **:** This case is not possible.

Case ii - $\lambda_1 = 0$**,**$P_S = 3C_{max}$**:** In this case D.5 becomes:

$$V_S - P_S = V_S - 3C_{max}$$

Case iii, iv - $\lambda_2 = 0$**,**$P_S = V_S$ **or** $P_S = V_S = 3C_{max}$**:** In these cases D.5 equals zero and thus they are minimum points.

Appendix E

Optimal Prices for Distributed Push Model with Known Costs

Optimal Prices for D Thus the maximization problem of D is formulated as follows:

$$\max_{P_D}(P_D - C_D)\frac{P_{Smax} - P_A - P_D(C_D)}{P_{Smax}} = G_{P_D}(P_D)$$

$$\mathrm{L} = (P_D - C_D)\frac{P_{Smax} - P_A - P_D(C_D)}{P_{Smax}} + \lambda_1(P_D - C_D)$$

$$\frac{\partial L}{\partial P_D} = \frac{P_{Smax} - P_A - 2P_D(C_D) + C_D}{P_{Smax}} + \lambda_1 = 0$$

s.t. $P_D - C_D \geq 0$, $\lambda_1 \geq 0$. According to the constraints, we have: $\lambda_1(P_D - C_D) = 0$, which gives us two possible solutions, i.e.$\lambda_1 = 0$ or $P_D = C_D$

Case i - $\lambda_1 = 0$**:** In this case, solving $\frac{\partial L}{\partial P_D} = 0$, we obtain $P_D^* = \frac{P_{Smax} - P_A + C_D}{2}$. Since the second derivative is negative in the entire interval, we have a maximum at the point where the first derivative vanishes. Since the first derivative indeed vanishes at the point derived above, thus it is a maximum point, as long as $P_D^* + P_A$ belongs to the interval $[0,\ P_{Smax}]$, as initially assumed.

We have to show that:

$P_D^* \geq C_D$ $P_D^* \geq C_D \Leftrightarrow P_{Smax} - P_A + C_D \geq 2C_D \Leftrightarrow P_{Smax} \ \geq P_A + C_D$, which is true due to our assumptions.

Next, we have to check that $P_D^* + P_A$ belongs to the interval $[0,\ P_{Smax}]$ as assumed above. First we show that:
$P_A + P_D^* \leq P_{Smax} \Leftrightarrow P_{Smax} - P_A + C_D + 2P_A \leq 2P_{Smax} \Leftrightarrow P_A + C_D \leq P_{Smax}$, which applies due to our assumptions. Also it is clear that $0 \leq P_A + P_D^*$, since both P_A and P_D^* are positive. (Recall that $P_D^* \geq C_D$.)

Case ii - $P_D = C_D$**:** if we substitute $P_D = C_D$ to $G_{P_D}(P_D)$ we result in $G_{P_D}(P_D) = 0$. Thus this is a minimum point.

Optimal Prices for A

Case 1 - P_A **is large enough, so that** $C_{max} \geq P_{Smax} - P_A$**:** In this case, the objective function of A becomes:

$$(P_A - C_A) \int_{c=0}^{P_{Smax}-P_A} \frac{(P_{Smax} - P_A - c)}{2P_{Smax}} = \frac{(P_A - C_A)(P_{Smax} - P_A)^2}{4P_{Smax}} = G_A(P_A)$$

$$\mathrm{L} = \frac{(P_A - C_A)(P_{Smax} - P_A)^2}{4P_{Smax}} - \lambda_1(P_A - C_A) - \lambda_2(P_{Smax} - P_A)$$

s.t. $P_A - C_A \geq 0$, $P_{Smax} - P_A \geq 0$.

$$\frac{\partial L}{\partial P_D} = \frac{P_{Smax}^2 - 4P_A P_{Smax} + 3P_A^2 + 2C_A P_{Smax} - 2P_A C_A}{4P_{Smax}} - \lambda_1 + \lambda_2$$

s.t. $P_A - C_A \geq 0$, $P_{Smax} - P_A \geq 0$, $\lambda_1, \lambda_2 \geq 0$.
According to the constraints, we have: $\lambda_1(P_A - C_A) = 0$, which gives us two possible solutions, i.e. $\lambda_1 = 0$ or $P_A = C_A$ and $\lambda_2(P_{Smax} - P_A) = 0$, which gives us another two possible solutions, i.e. $\lambda_2 = 0$ or $P_A = P_{Smax}$ Thus we have the following four cases.

Case i - $\lambda_1 = 0$ **and** $\lambda_2 = 0$**:** In this case solving $\frac{\partial L}{\partial P_D} = 0$, we obtain two possible solutions for P_A, namely $P_{Smax}\frac{(2C_A + P_{Smax})}{3}$.

Case ii - $\lambda_1 = 0$ **and**$P_A = P_{Smax}$**:** then and $G_A(P_A) = 0$.

Case iii - $\lambda_2 = 0$ **and** $P_A = C_A$**:** then again $G_A(P_A) = 0$.

Case iv - $P_A = P_{Smax}$ **and** $P_A = C_A$**:** This case can only apply if by coincidence $P_{Smax} = C_A$. But even then A does not have any option in choosing P_A, except for $P_A = C_A$, which is the same as in ii.

Thus, the only maximizing solution is $P_A^* = \frac{(2C_A+P_{Smax})}{3}$, where $G_A = \frac{(P_{Smax}-C_A)^3}{54P_{Smax}}$. Under this P_A^*, $G_A \geq 0$ provided that $P_{Smax} \geq C_A$. In the opposite case the service cannot be offered, and thus $P_{Smax} \geq C_A$ is assumed. Note also that, for the same reason, $P_A^* > C_A$ and $P_A^* < P_{Smax}$ as required by the constraints. We have to check the condition under which $C_{max} \geq P_{Smax} - P_A^*$:

$$C_{max} \geq P_{Smax} - P_A^* \Leftrightarrow$$

$$C_{max} \geq P_{Smax} - \frac{(2C_A + P_{Smax})}{3} \Leftrightarrow$$

$$\frac{3C_{Max}}{2} \geq P_{Smax} - C_A.$$

Note that this condition is verifiable by A. If this is not the case, then the objective function is decreasing with P_A in the entire interval $[P_{Smax} - C_{max},\ P_{Smax}]$ and thus the maximum point for this case is $P_{Smax} - C_{max}$, provided that it is positive. However, this point is also permissible under the next case, because it is on the border of the two intervals considered, and thus it is superseded by the optimal choice below.

Case 2 - P_A **is small enough so that** $C_{max} \leq P_{Smax} - P_A$**:** In this case, the objective function of A becomes:

$$(P_A - C_A)\int_{c=0}^{C_{max}} \frac{(P_{Smax} - P_A - c)}{2P_{Smax}} = \frac{(P_A - C_A)(2C_{max}(P_{Smax} - P_A) - C_{max}^2)}{4P_{Smax}} = G_{A2}(P_A)$$

$$\mathrm{L} = \frac{(P_A - C_A)(2C_{max}(P_{Smax} - P_A) - C_{max}^2)}{4P_{Smax}} - \lambda_1(P_A - C_A) - \lambda_2(P_{Smax} - P_A),$$

s.t. $P_A - C_A \geq 0$, $P_{Smax} - P_A \geq 0$.

$$\frac{\partial L}{\partial P_D} = \frac{2C_{max}P_{Smax} - 4C_{max}P_A - C_{max}^2 + 2C_{max}C_A}{4P_{Smax}} - \lambda_1 + \lambda_2$$

s.t. $P_A - C_A \geq 0$, $P_{Smax} - P_A \geq 0$, $\lambda_1 \geq 0$, $\lambda_2 \geq 0$. According to the constraints, we have: $\lambda_1(P_A - C_A) = 0$, which gives us two possible solutions, i.e.$\lambda_1 = 0$ or $P_A = C_A$ and $\lambda_2(P_{Smax} - P_A) = 0$, which gives us another two possible solutions, i.e. $\lambda_2 = 0$ or $P_A = P_{Smax}$.

Case i - $\lambda_1 = 0$ and $\lambda_2 = 0$: In this case solving $\frac{\partial L}{\partial P_D} = 0$, we obtain $P_{A2}^* = \frac{2P_{Smax} - C_{max} + 2C_A}{4}$.

Case ii - $\lambda_1 = 0$ and $P_A = P_{Smax}$: In this case $G_{A2}(P_A) = \frac{-C_{max}^2(P_{Smax} - C_A)}{4P_{Smax}}$, which is negative since $P_{Smax} \geq P_A \geq C_A$

Case iii - $\lambda_2 = 0$ and $P_A = C_A$: In this case $G_{A2}(P_A) = 0$

Thus the optimal choice is $P_{A2}^* = \frac{2P_{Smax} - C_{max} + 2C_A}{4}$. Note that $P_{A2}^* < P_{Smax}$ as required by the constraints. Indeed, this inequality is equivalent to:

$$\frac{2P_{Smax} - C_{max} + 2C_A}{4} < P_{Smax} \Leftrightarrow$$

$$C_A - P_{smax} < \frac{C_{max}}{2}$$

which is obvious because the lefthand quantity is negative. Also, we have to check the inequality $P_{A2}^* \geq C_A$.

$$\frac{2P_{Smax} - C_{max} + 2C_A}{4} \geq C_A$$

$$P_{Smax} - C_A \geq \frac{C_{max}}{2}$$

Thus if this inequality is true, then P_{A2}^* is a maximum point. Next, we check under what conditions $C_{max} \leq P_{Smax} - P^*_{A2}$:

$$C_{max} \leq P_{Smax} - P^*_{A2}$$

$$\frac{3C_{Max}}{2} \leq P_{Smax} - C_A$$

If this inequality is true (and thus the previous one, which is weaker) then P^*_{A2} is a maximum point. In case this inequality is not true then the maximum point is the one derived in the previous case.

Appendix F

Optimal Prices for Distributed Push Model with Unknown Costs

Optimal Prices for D Solving we obtain the following points.

Case i - $\lambda_1 = 0$**:** In this case, solving $\frac{\partial L}{\partial P_D} = 0$, we obtain $P_D^* = \frac{P_{Smax} - P_A + C_D}{2}$. Since the second derivative is negative in the entire interval, we have a maximum at the point where the first derivative vanishes. Since the first derivative indeed vanishes at the point derived above, thus it is a maximum point, as long as $P_D^* + P_A$ belongs to the interval $[0,\ P_{Smax}]$, as initially assumed. We have to show that $P_D^* \geq C_D$:

$$P_D^* \geq C_D \Leftrightarrow$$

$$P_{Smax} - P_A + C_D + 2P_A \leq 2P_{Smax} \Leftrightarrow$$

$$P_A + C_D \leq 2P_{Smax}$$

which applies due to our assumptions. Also it is clear that $0 \leq P_A + P_D^*$, since both P_A and P_D^* are positive. (Recall that $P_D^* \geq C_D$.)

Case ii - $P_D = C_D$**:** If we substitute $P_D = C_D$ to $G_{P_D}(P_D)$ we result in $G_{P_D}(P_D) =$

0. Thus this is a minimum point.

Optimal Prices for A

Case 1 - P_A is large enough, so that $C_{max} \geq P_{Smax} - P_A$: The objective function of A becomes:

$$(P_A - C_A) \int_0^{P_{Smax}-P_A} \frac{P_{Smax} - P_A - c}{2P_{Smax}} dc = \frac{(P_A - C_A)(P_{Smax} - P_A)^2}{4P_{Smax}} \tag{F.1}$$

Solving again the Lagrangian function we have:

$$\mathrm{L} = \frac{(P_A - C_A)(P_{Smax} - P_A)^2}{4P_{Smax}} - \lambda_1(P_A - C_A) - \lambda_2(P_{Smax} - P_A)$$

s.t. $P_A - C_A \geq 0$, $P_{Smax} - P_A \geq 0$.

$$\frac{\partial L}{\partial P_A} = \frac{P_{Smax}^2 - 4P_A P_{Smax} + 3P_A^2 + 2C_A P_{Smax} - 2P_A C_A}{4P_{Smax}} - \lambda_1 + \lambda_2$$

s.t. $P_A - C_A \geq 0$, $P_{Smax} - P_A \geq 0$, $\lambda_1 \geq 0$, $\lambda_2 \geq 0$. According to the constraints we have $\lambda_1(P_A - C_A) = 0$ and $\lambda_2(P_{Smax} - P_A) = 0$, which give us four possible combinations.

Case i - $\lambda_1, \lambda_2 = 0$: In this case solving the $\frac{\partial L}{\partial P_A} = 0$, we obtain two possible solutions for P_A, namely P_{Smax} and $\frac{2C_A + P_{Smax}}{3}$. For $P_A = P_{Smax}$ though, we have a minimum point since **??** equals zero.

Case ii - $\lambda_1 = 0$ and $P_A = P_{Smax}$: In this case **??** equals zero and thus this is a minimum point.

Case iii - $\lambda_2 = 0$ and $P_A = C_A$: In this case again **??** equals zero and thus this is a minimum point.

Case iv - $P_A = P_{Smax}$ and $P_A = C_A$: This case can only apply if by coincidence $P_{Smax} = C_A$. But even then A does not any option in choosing P_A, except for $P_A = C_A$, which is the same as Case iii.

Thus the only maximizing solution is $P_A^* = \frac{2C_A + P_{Smax}}{3}$, where **??**$= \frac{(P_{Smax} - C_A)^2}{54 P_{Smax}}$. Under this P_A^*, **??** ≥ 0 provided that $P_{Smax} \geq C_A$. In the opposite case the service cannot be offered, and thus $P_{Smax} \geq C_A$ is assumed. Not also that, for the same reason, $P_A^* > C_A$ and $P_A^* < P_{Smax}$ are true, as required by the constraints. We have to check the condition under which $C_{max} \geq P_{Smax} - P_A^*$.

$$C_{max} \geq P_{Smax} - P_A^* \Leftrightarrow$$

$$C_{max} \geq P_{Smax} - \frac{2C_A + P_{Smax}}{3}$$

$$\frac{3C_{max}}{2} \geq P_{Smax} - C_A$$

Note that this condition is verifiable by A. If this is not the case, then the objective function is decreasing with P_A in the entire interval $[P_{Smax} - C_{max},\ P_{Smax}]$ and thus the maximum point in this case is $P_{Smax} - C_{max}$, provided that is positive, However, this point is also permissible under the next case (Case 2), because it is on the border of the two intervals considered, and this it is superseded by the optimal choice below.

Case 2 - P_A is small enough so that $C_{max} \leq P_{Smax} - P_A$: The objective function of A becomes:

$$(P_A - C_A) \int_{c=0}^{C_{max}} \frac{P_{Smax} - P_A - c}{2P_{Smax}} dc = \frac{(P_A - C_A)(2C_{max}(P_{Smax} - P_A) - C_{max}^2)}{4P_{Smax}} \tag{F.2}$$

Solving again the Lagrangian function we have:

$$\text{L} = \frac{(P_A - C_A)(2C_{max}(P_{Smax} - P_A) - C_{max}^2)}{4P_{Smax}} - \lambda_1(P_A - C_A) - \lambda_2(P_{Smax} - P_A)$$

s.t. $P_A - C_A \geq 0$, $P_{Smax} - P_A \geq 0$.

$$\frac{\partial L}{\partial P_A} = \frac{2C_{max}P_{Smax} - 4C_{max}P_A - C_{max}^2 + 2C_{max}C_A}{4P_{Smax}} - \lambda_1 + \lambda_2$$

s.t. $P_A - C_A \geq 0$, $P_{Smax} - P_A \geq 0$, $\lambda_1 \geq 0$, $\lambda_2 \geq 0$. According to the constraints we have $\lambda_1(P_A - C_A) = 0$ and $\lambda_2(P_{Smax} - P_A) = 0$, which give us four possible combinations.

Case i - $\lambda_1, \lambda_2 = 0$**:** In this case solving the $\frac{\partial L}{\partial P_A} = 0$, we obtain $P_A^* = \frac{2P_{Smax}^2 - C_{max} + 2C_A}{4}$.

Case ii - $\lambda_1 = 0$ **and** $P_A = P_{Smax}$**:** In this case **??** $= \frac{-C_{max}^2(P_{Smax} - C_A)}{4P_Smax}$, which is negative since $P_{Smax} \geq P_A \geq C_A$.

Case iii - $\lambda_2 = 0$ **and** $P_A = C_A$**:** In this case again **??** equals zero and thus this is a minimum point.

Case iv - $P_A = P_{Smax}$ **and** $P_A = C_A$**:** This case can only apply if by coincidence $P_{Smax} = C_A$. But even then A does not any option in choosing P_A, except for $P_A = C_A$, which is the same as Case iii.

Thus the optimal choice is $P_A^* = \frac{2P_{Smax}^2 - C_{max} + 2C_A}{4}$. Note that $P_A^* < P_{Smax}$ is true as required by the constraints. Indeed, the inequality is equivalent to:

$$\frac{2P_{Smax}^2 - C_{max} + 2C_A}{4} < P_{Smax} \Leftrightarrow$$

which is obvious because the left-hand quantity is negative. Also we have to check the inequality $P_A^* \geq C_A$.

$$\frac{2P_{Smax}^2 - C_{max} + 2C_A}{4} \geq C_A \Leftrightarrow$$

$$P_{Smax} - C_A \geq \frac{3C_{max}}{2},$$

If this inequality is true (and thus the previous one, is weaker) then P_A^* is a maximum point. In case this inequality is not true then the maximum point is the one derived in the previous case.

Appendix G

Analysis of Efficiency

Calculation of Probability[Service] in Collaborative Scenario $\Pr[C_D + C_A \leq P_S]$

Case A - $P_{Smax} < C_{max}$**:**

$$\int_0^{P_{Smax}} F_W(p) f_{P_S}(p) dp = \int_0^{P_{Smax}} \frac{p^2}{2P_{Smax}C_{max}^2} dp = \frac{P_{Smax}^2}{6C_{max}^2}$$

Case B - $C_{max} \leq P_{Smax} < 2C_{max}$**:**

$$\int_0^{P_{Smax}} F_W(p) f_{P_S}(p) dp = \int_0^{C_{max}} \frac{p^2}{2P_{Smax}C_{max}^2} dp +$$

$$+ \int_{C_{max}}^{P_{Smax}} \frac{1}{P_{Smax}} (\frac{2p}{C_{max}} - \frac{p^2}{2C_{max}^2} - 1) dp =$$

$$= \frac{C_{max}^3}{6C_{max}^2 P_{Smax}} + \frac{2P_{Smax}^2}{2C_{max}P_{Smax}} - \frac{P_{Smax}^3}{6C_{max}^2 P_{Smax}} -$$

$$- \frac{P_{Smax}}{P_{Smax}} - \frac{2C_{max}^2}{2C_{max}P_{Smax}} + \frac{C_{max}^3}{6C_{max}^2 P_{Smax}} + \frac{C_{max}}{P_{Smax}} =$$

$$= \frac{2C_{max}^3 - P_{Smax}^3 + 6C_{max}(P_{Smax}^2 - C_{max}^2) + 6C_{max}^2(C_{max} - P_{Smax})}{6C_{max}^2 P_{Smax}} =$$

$$= \frac{2C_{max}^3 - P_{Smax}^3 + 6C_{max}P_{Smax}(P_{Smax} - C_{max})}{6C_{max}^2 P_{Smax}}$$

Case C - $2C_{max} \leq P_{Smax}$**:**

$$\int_0^{P_{Smax}} F_W(p) f_{P_S}(p)dp = \int_0^{C_{max}} \frac{p^2}{2P_{Smax}C_{max}^2}dp +$$

$$\int_{C_{max}}^{2C_{max}} \frac{1}{P_{Smax}}\left(\frac{2p}{C_{max}} - \frac{p^2}{2C_{max}^2} - 1\right)dp + \int_{2C_{max}}^{P_{Smax}} \frac{1}{P_{Smax}}dp =$$

$$= \frac{C_{max}^3}{6C_{max}^2 P_{Smax}} + \frac{C_{max}^2}{2C_{max}P_{Smax}} - \frac{C_{max}^3}{6C_{max}^2 P_{Smax}} - \frac{C_{max}}{P_{Smax}} - \frac{C_{max}^2}{2C_{max}P_{Smax}} +$$

$$+ \frac{C_{max}^3}{6C_{max}^2 P_{Smax}} + \frac{C_{max}}{P_{Smax}} + \frac{P_{Smax}}{P_{Smax}} - \frac{C_{max}}{P_{Smax}} = \frac{P_{Smax} - C_{max}}{P_{Smax}}$$

All of the above integrals can be calculated in closed forms.

Calculation of Probability[Service] in Distributive Scenario Pr$[P_A^* + P_D^* \leq P_S]$

Case A - $2P_{Smax}/3 \leq 2C_{max}$ **and** $P_{Smax} < 2C_{max}$**:**

$$\int_0^{P_{Smax}} F_R(p) f_{P_S}(p)dp = \int_{p=\frac{2P_{Smax}}{3}}^{P_{Smax}} \frac{(6p - 4P_{Smax})^2}{12C_{max}^2 P_{Smax}}dp =$$

$$= \frac{P_{Smax}^3}{C_{max}^2 P_{Smax}} - \frac{2P_{Smax}^3}{C_{max}^2 P_{Smax}} + \frac{4P_{Smax}^3}{3C_{max}^2 P_{Smax}} - \left(\frac{8P_{Smax}^3}{27C_{max}^2 P_{Smax}} - \frac{8P_{Smax}^3}{9C_{max}^2 P_{Smax}} + \frac{8P_{Smax}^3}{9C_{max}^2 P_{Smax}}\right) =$$

$$= \frac{P_{Smax}^2}{27C_{max}^2}$$

Case B - $2P_{Smax}/3 \leq 2C_{max}$ **and** $2C_{max} \leq P_{Smax} < 3C_{max}$**:**

$$\int_0^{P_{Smax}} F_R(p) f_{P_S}(p)dp = \int_{p=\frac{2P_{Smax}}{3}}^{2C_{max}} \frac{(6p - 4P_{Smax})^2}{12C_{max}^2 P_{Smax}}dp +$$

$$+\int_{p=C_{max}}^{2P_{Smax}} \frac{6p-4P_{Smax}-C_{max}}{3C_{max}P_{Smax}}dp =$$

$$= \frac{8C_{max}^3}{C_{max}^2 P_{Smax}} - \frac{8C_{max}^2 P_{Smax}}{C_{max}^2 P_{Smax}} + \frac{8P_{Smax}^2 C_{max}}{3C_{max}^2 P_{Smax}} - \left(\frac{8P_{Smax}^3}{27C_{max}^2 P_{Smax}} - \frac{8P_{Smax}^3}{9C_{max}^2 P_{Smax}} + \frac{8P_{Smax}^3}{9C_{max}^2 P_{Smax}}\right)+$$

$$+\frac{P_{Smax}^2}{C_{max}P_{Smax}} - \frac{4P_{Smax}^2}{3C_{max}P_{Smax}} - \frac{P_{Smax}C_{max}}{3C_{max}P_{Smax}} - \left(\frac{4C_{max}^2}{C_{max}P_{Smax}} - \frac{8P_{Smax}C_{max}}{3C_{max}P_{Smax}} - \frac{2C_{max}^2}{3C_{max}P_{Smax}}\right) =$$

$$= \frac{(6C_{max}-2P_{Smax})^3}{27C_{max}^2 P_{Smax}} - \frac{P_{Smax}^2 + 10C_{max}^2 - 7P_{Smax}C_{max}}{3C_{max}P_{Smax}} =$$

$$= \frac{-8P_{Smax}^3 + 63P_{Smax}^2 C_{max} - 153P_{Smax}C_{max}^2 + 126C_{max}^3}{27C_{max}^2 P_{Smax}}$$

Case C - $2C_{max} \leq 2P_{Smax}/3 < 3C_{max}$ **and** $3C_{max} \leq P_{Smax} < 4.5C_{max}$**:**

$$\int_{0?}^{P_{Smax}} F_R(p) f_{P_S}(p)dp = \int_{p=\frac{2P_{Smax}}{3}}^{3C_{max}} \frac{6p-4P_{Smax}-C_{max}}{3C_{max}P_{Smax}}dp+$$

$$+\int_{p=3C_{max}}^{P_{Smax}} \frac{10C_{max}(6p-4P_{Smax})-(6p-4P_{Smax})^2-13C_{max}^2}{12C_{max}^2 P_{Smax}}dp$$

We substitute $(6p-4P_{Smax}) = u$ and thus $du = \frac{1}{6}dp$. Hence we have:

$$\int_0^{18C_{max}-4P_{Smax}} \frac{u-C_{max}}{18C_{max}P_{Smax}}du + \int_{18C_{max}-4P_{Smax}}^{2P_{Smax}} \frac{10C_{max}u-u^2-13C_{max}^2}{72C_{max}^2 P_{Smax}}du =$$

$$= -\frac{34}{9} + \frac{4P_{Smax}}{9C_{max}} + \frac{8C_{max}}{P_{Smax}} - \frac{109}{12} - \frac{P_{Smax}^2}{3C_{max}^2} + \frac{19P_{Smax}}{6C_{max}} + \frac{31C_{max}}{4P_{Smax}}$$

$$= \frac{-12P_{Smax}^3 + 130P_{Smax}^2 C_{max} - 463P_{Smax}C_{max}^2 + 567C_{max}^3}{36C_{max}^2 P_{Smax}}$$

Case D - $3C_{max} \leq 2P_{Smax}/3 < \frac{10C_{max}}{3}$ **and** $4.5C_{max} \leq P_{Smax} < 5C_{max}$**:**

$$\int_{2P_{Smax}/3}^{P_{Smax}} F_R(p) f_{P_S}(p)dp = \int_{p=\frac{2P_{Smax}}{3}}^{P_{Smax}} \frac{10C_{max}(6p-4P_{Smax})-(6p-4P_{Smax})^2-13C_{max}^2}{12C_{max}^2 P_{Smax}}dp$$

After substitution we have:

$$\int_{u=0}^{2P_{Smax}} \frac{10uC_{max} - u^2 - 13C_{max}^2}{72C_{max}^2 P_{Smax}} = \frac{20C_{max}P_{Smax}^2}{72C_{max}^2 P_{Smax}} - \frac{8P_{Smax}^3}{216C_{max}^2 P_{Smax}} - \frac{26C_{max}^2 P_{Smax}}{72C_{max}^2 P_{Smax}} =$$

$$= \frac{30C_{max}P_{Smax} - 39C_{max}^2 - 4P_{Smax}^2}{108C_{max}^2}$$

Case E - $\frac{10C_{max}}{3} \leq 2P_{Smax}/3 < 5C_{max}$ **and** $P_{Smax} \geq 5C_{max}$ **:**

$$\int_{2P_{Smax}/3}^{5C_{max}} F_R(p) f_{P_S}(p) dp = \int_{p=\frac{2P_{Smax}}{3}}^{5C_{max}} \frac{10C_{max}(6p - 4P_{Smax}) - (6p - 4P_{Smax})^2 - 13C_{max}^2}{12C_{max}^2 P_{Smax}} dp$$

After substitution we have:

$$\int_{u=0}^{30C_{max}-4P_{Smax}} \frac{10uC_{max} - u^2 - 13C_{max}^2}{72P_{Smax}C_{max}^2} du + \int_{30C_{max}-4P_{Smax}}^{2P_{Smax}} \frac{1}{P_{Smax}} du =$$

$$= \frac{613}{18} + \frac{8P_{Smax}^2}{27C_{max}^2} - \frac{50P_{Smax}}{9C_{max}} - \frac{815C_{max}}{12P_{Smax}} + \frac{6P_{Smax} - 30C_{max}}{6P_{Smax}} =$$

$$= \frac{32P_{Smax}^3 - 600C_{max}P_{Smax}^2 + 3786C_{max}^2 P_{Smax} - 7875C_{max}^3}{108C_{max}^2 P_{Smax}}$$

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