Differentiated Traffic-based Interconnection Agreements for Next Generation Networks

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"I am enough of an artist to draw freely upon my imagination."

Albert Einstein

Abstract

Ruzana Davoyan

The issue of inter-provider cost distribution in international interconnection has been a subject of intense debate in the past few years. For various reasons, developing countries have had to bear high costs for international Internet connectivity. The transition of communication networks to IP-based networks enhances the urgency to resolve the apparent lack of fairness in international interconnection. This is due to the development of cheap technologies for voice communications, which reduces the revenues of developing countries received from international telephone calls, and at the same time, places the burden of international Internet connectivity costs on developing countries.

There exists a large body of literature toward achieving the equitable and sustainable expansion of infrastructures in developing countries. It is mainly focused on proposing interconnection pricing schemes. However, the existing approaches strike the balance between the two objectives of interconnection pricing, viz., competition development and profitability quite differently. Hence, no single solution has a clear advantage over the others. The alternative approach towards solving the interconnection cost-sharing problem involves compensating each provider for the costs that it incurs in carrying traffic generated by other providers. However, compensation between providers cannot be solely done based on the traffic flows, because it provides a poor basis for allocating any costs. In the Internet, it is not clear who originally initiated a transmission, and therefore, who should pay for the costs.

The key contribution of this dissertation is to support the development and profitability of the communications market by reducing the existing imbalance in the interconnection cost allocation. A novel technique called Differentiated Traffic-based Interconnection Agreement (DTIA) was proposed. The key idea behind DTIA is that instead of performing intercarrier compensation based on traffic flows, compensation is performed based on the original initiator of a transmission. Determination of a transmission initiator in packet-switched networks is a complicated task that deals with technical issues and considerable costs. We have tackled this challenge by marking the information about the transmission initiator in the IP packet header, and have proposed a traffic differentiation mechanism that has low computational complexity. In DTIA, providers get compensated differently for traffic originally initiated by their own customers, as opposed to traffic initiated by customers of other networks. Such an approach stimulates the development of market by ensuring that each provider is compensated for utilization of its infrastructure.

In order to evaluate the differentiated traffic-based approach, we formulated economic models and analyzed their behaviors from different perspectives. Compared to existing solutions, the DTIA model enhances the economic efficiency of the market by improving social welfare.

Zusammenfassung

Ruzana Davoyan

In den letzten Jahren war die Kostenverteilung von Zwischenanbietern bei internationalen Internetverbindungen ein viel diskutiertes Thema. Aus verschiedenen Gründen mussten Entwicklungsländer hohe Kosten für internationale Internetverbindungen tragen. Der Übergang von Kommunikationsnetzwerken zu IP-basierten Netzwerken erhöht den Druck, den offensichtlichen Mangel an Gerechtigkeit bei internationalen Internetverbindungen zu beheben. Dies ist durch die Entwicklung von kostengünstigen Technologien für Sprachkommunikationen bedingt, welche die durch internationale Telefongespräche erzielbaren Einkünfte von Entwicklungsländern reduzieren und zugleich den Entwicklungsländern die Bürde der stark zunehmenden internationalen Internetverbindungskosten auferlegen.

Es gibt viel Literatur darüber, wie ein gerechter und zukunftsfähiger Ausbau des Internets in Entwicklungsländern erreicht werden kann. Diese richten sich im Wesentlichen darauf, Schemata für Verbindungspreise vorzuschlagen. Nichtsdestoweniger ziehen die existierenden Ansätze ziemlich unterschiedliche Bilanz zwischen den beiden Zielen der Verbindungspreisermittlung, nämlich Wettbewerbsentwicklung und Rentabilität. Infolgedessen hat kein einzelnes Lösungskonzept einen klaren Vorteil gegenüber den anderen. Ein alternativer Ansatz, um das Problem der Verteilung der Verbindungskosten zu lösen, beinhaltet den Ausgleich der Kosten von jedem Anbieter, die er übernimmt, indem er Datenverkehr überträgt, welcher von anderen Anbietern generiert wurde. Dennoch kann der Abgleich zwischen Anbietern nicht nur auf Grund der IP-Verkehrsflüsse durchgeführt werden, da dies, wie wir zeigen werden, eine schlechte Grundlage für die Verteilung der Kosten bietet. Im Internet ist nämlich nicht klar, wer ursprünglich eine Übertragung initiiert hat und demzufolge, wer die Kosten bezahlen soll.

Der wesentliche Beitrag dieser Dissertation ist es, die Entwicklung und Rentabilität des Kommunikationsmarktes zu fördern, indem das bestehende Ungleichgewicht in der Verteilung von Verbindungskosten auf die Service-Provider reduziert wird. Wir schlagen ein neues Verfahren namens “Differentiated Traffic-based Interconnection Agreement (DTIA)” vor. Der Grundidee von DTIA besteht darin, anstatt einen Ausgleich von Zwischenträgern basierend auf dem IP-Datenstrom durchzuführen, die Kompensation aufgrund des ursprünglichen Initiators einer Übertragung IP-vorzunehmen. Die Bestimmung des Initiators einer Übertragung in paketvermittelten Netzwerken ist eine komplizierte Aufgabe, bei der technische Aspekte und beträchtliche Kosten berücksichtigt werden müssen. In dieser Dissertation wurde diese Herausforderung gelöst, indem

die Informationen über den Übertragungsinitiator im IP-Paketkopf markiert werden. Zusätzlich wurde ein Verfahren zur Differentiation von Datenströmen vorgeschlagen, das eine geringe rechnerische Komplexität hat. In DTIA werden Anbieter unterschiedlich für den Datenverkehr vergütet, abhängig davon, ob dieser ursprünglich von ihren eigenen Kunden oder von Kunden anderer Netzwerke initiiert wurde. Ein solcher Ansatz kurbelt die Marktentwicklung an, indem er sicherstellt, dass jeder Anbieter für die Nutzung seiner Infrastruktur vergütet wird.

Um den auf differenziertem Datenverkehr basierenden Ansatz zu bewerten, haben wir analytische wirtschaftliche Modelle erstellt und ihre Verhaltensweisen analysiert. Wir zeigen mithilfe dieser Modelle, dass unser DTIA-Modell die wirtschaftliche Markteffizienz in Bezug auf die soziale Wohlfahrt im Vergleich mit existierenden Lösungen steigert.

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Abbreviations

AC	Access Charge
AFRISPA	African Internet Service Providers Association
APEC	Asia-Pacific Economic Cooperation
ARPA	Advanced Research Projects Agency
ARPANET	Advanced Research Projects Agency Network
AS	Autonomous System
BAK	Bill and Keep
BGP	Border Gateway Protocol
BLPA	Bilateral Peering Arrangement
CIX	Commercial Internet Exchange
CPNP	Calling Party's Network Pays
DF	Don't Fragment
DT	Differentiated Traffic
DTIA	Differentiated Traffic-based Interconnection Agreement
ECPR	Efficient Component Pricing Rule
FCC	Federal Communications Commission
FTP	File Transfer Protocol
IBP	Internet Backbone Provider
ICAIS	International Charging Arrangements for Internet Services
ICT	Information and Communication Technologies
IP	Internet Protocol
IPv4	Internet Protocol Version 4
IPv6	Internet Protocol Version 6
ISP	Internet Service Provider
ITU	International Telecommunication Union

ITU-T	International Telecommunications Union - Telecommunications Standardization Sector
IXC	Inter-exchange Carrier
LEC	Local Exchange Carrier
LRIC	Long-run Incremental Cost
ML	Membership Label
MLPA	Multilateral Peering Arrangement
MTU	Maximum Transfer Unit
NAP	Network Access Point
NBS	Nash Bargaining Solution
NGN	Next Generation Network
NSF	National Science Foundation
NSFNET	National Science Foundation Network
OSI	Open System Interconnection
P2P	Peer-to-Peer
PPB	Provider-to-Provider Border
PSTN	Public Switched Telephone Network
QoS	Quality of Service
SG3	Study Group 3
SKA	Sender Keep All
SLA	Service Level Agreement
TCP	Transmission Control Protocol
TF	Traffic Flow
UDP	User Datagram Protocol
VoIP	Voice over IP
WTSA	World Telecommunications Standardization Assembly

To my sister Kristina

Chapter 1

Introduction

"If you can't explain it simply, you don't understand it well enough."

Albert Einstein

The telecommunications market comprised of a variety of communications networks enables any network to convey information to others. The establishment of communication between networks is referred to as *interconnection*. International interconnection has been a subject of debate from economic, technical, and regulatory perspectives in the past few years.

This dissertation is focused on interconnection economics in Next Generation Networks (NGNs), which present the migration of circuit-switched networks to packet-based networks using Internet Protocol (IP). According to the International Telecommunication Union (ITU, the United Nations agency) the term *NGN* is defined as follows:

"A Next Generation Network (NGN) is a packet-based network able to provide services including Telecommunication Services and able to make use of multiple broadband, QoS-enabled transport technologies and in which service-related functions are independent from underlying transport-related technologies. It offers unrestricted access by users to different service providers. It supports generalized mobility which will allow consistent and ubiquitous provision of services to users."

The convergence of networks (i.e., the shift towards IP-based networks) raises the question whether NGN interconnection should be based on the economics of interconnection in traditional telephony or in IP networks to ensure overall efficiency and transparency of the communications market [62], [60]. Unlike traditional telephony, which is highly regulated, the Internet interconnection is not subject to any regulation and is a matter of private bilateral negotiations [3], [56]. The regulation of interconnection is the most important issue of regulators with regard to the development of competition on the telecommunications market. Interconnection regulation is mainly achieved by *determining interconnection obligations and controlling interconnection pricing*. Determining *interconnection charges* is the most controversial issue of telecommunications regulation, because it affects both the level of competition and returns on investments [37], [50].

Setting high interconnection rates stimulates high returns on investments. This is attractive to the incumbent providers, who invested in their infrastructures, however, discourages entry or expansion of the market [37]. On the other side, establishing low interconnection charges is thought to favour entrants, but can discourage investments of the incumbents in infrastructure. Thus, the purpose of regulation of interconnection prices is to promote service-based competition and to encourage investments into infrastructure. Interconnection prices play an important role in the total cost of delivering telecommunications services to customers.

Generally, regulators consider four main *interconnection pricing* approaches, namely historical cost-based pricing, Long-run Incremental Cost (LRIC) pricing, Efficient Component Pricing Rule (ECPR), and peering arrangements (or Bill and Keep). The range of existing solutions to the interconnection pricing is described in [64]. These approaches do not achieve the two objectives of interconnection pricing, viz., competition development and profitability simultaneously. Hence, no single method has a clear advantage over the others. For example, LRIC stimulates competition by new entrants in the downstream market. However, this is only achieved under a number of unrealistic/limited circumstances, and in reality, the LRIC scheme might induce inefficiencies. The detailed analyses are provided in [4], [33], [2], [50].

International Internet interconnection is mainly based on the *transit relationships*, where a customer provider pays a transit provider to deliver traffic between customers. Such a cost distribution model with unilateral settlements (i.e., the transit model) makes the access and the use of the Internet more expensive for customers, in particular in low income developing countries [35]. The interconnection challenges in developing countries, in particular in Africa, have been extensively studied in [10], [30], [58], [43], [60], [61]. The problem concerns the net cash flow that flows from developing to developed worlds. In telephony, for example, it is acceptable that more than 50% of rural providers' revenues in developing countries could come from incoming calls [10]. In fact, the number of incoming calls is higher than the number of outgoing calls, which is mainly explained by affordability of the urban customers. Such a traffic imbalance between areas with different level of affordability and willingness to pay is also true for the international calls. In contrast to the telephony example, in the Internet, the customer provider pays for sent and received traffic. Moreover, the estimations of ITU-T Study Group 3 showed that due to the development of cheap technologies for voice communications (e.g., voice over IP, VoIP), the payments of developing countries for traffic exchange may increase [58]. Hence, the migration towards NGNs enhances the urgency to resolve international Internet interconnection issues.

In recent years, some non-US carriers, especially from the Asia-Pacific region, complained about unfair sharing of the international transmission capacity costs. Asia-Pacific carriers, which arranged transit relationships with the US carriers, pay for the both ends of international connectivity to the United States, i.e., cover 100% of the cost of international link as well as transit fees. The study [52] that investigated the interconnection issues claimed that there is no anti-competitiveness against international carriers in interconnection arrangements, and that U.S. Internet backbones deal with domestic and foreign backbones in the same way.

Since 1998 ITU has studied the issue of international interconnection cost sharing. More specifically, in 1998 APEC has raised this issue during the debate, known as International Charging Arrangements for Internet Services (ICAIS). Later in 2000, ITU adopted the recommendation D.50 that pursued to encourage providers to adopt symmetric peering (settlement-free) arrangements [51]. This is due to the perception that regulators cannot measure the interconnection costs correctly, and historically, set interconnection prices, which exceed the real costs [40]. However, various FCC studies showed that support of a symmetric peering is lacking, and commercial agreements are dominant. Attempts to impose peering creates disincentive for larger providers to invest in further infrastructure because smaller providers can abuse this investment without investing of their own.

In 2000, the Sector ITU-T Study Group 3 adopted a proposal, introduced by the Asia and Oceania Region tariff group, which recommended the establishment of bilateral arrangements and the compensation of each provider to be based on the costs that it incurs in carrying traffic generated by the other network [52]. More specifically, the Asia-Pacific carriers argued to assign benefits or costs of interconnection based on flows of traffic. In response to this, the USA submitted to the ITU World Telecommunications Standardization Assembly (WTSA) "formal contributions in opposition to both the substance of this recommendation and the procedures used in its adoption" [52]. Indeed, traffic flows are not a reasonable indicator to share the costs, since in the Internet it is not clear who originally initiated a transmission and, therefore, who should pay for the costs. An incoming packet to Taiwan from the USA, may be i) either part of a transmission, such as a webpage that was requested by a user in Taiwan or ii) part of a transmission, such as an email that was sent by a customer in the U.S. Moreover, in some cases, U.S. backbones accept traffic from one Asia-Pacific region that is forwarded to another Asia-Pacific region. In this case, U.S. customers do not benefit from this traffic. Overall, it can be concluded that compensation between Internet providers cannot be solely done based on the traffic flows, which provide a poor basis for cost sharing. In addition to this, “backbones negotiating an interconnection arrangement consider, among other things, relative infrastructure investments as well as the composition and location of customers and content providers” [52]. The current program of the ITU-T Study Group 3 for the Study Period 2009-2012 continues to examine international Internet connectivity aspects meeting the standardization challenges.

To summarize, two key challenges that remain in international Internet interconnection are i) an imbalance in the allocation of interconnection cost, and ii) a scarcity of cheap international connectivity. Under such circumstances “there are serious structural problems in supporting a highly diverse and well populated” global service provider industry [49]. Thus, the adaptation of the interconnection arrangement that stimulates equitable cost distribution between a wide diversity of players both large and small, remains an open issue.

1.1 Research Question

The research objective of this dissertation is formulated in the following research question:

- How should we balance the allocation of the Internet interconnection costs in order to improve the economic efficiency ?

Economic efficiency refers to the allocation of resources that maximizes social welfare of a system. We evaluate the efficiency of the proposed in this thesis model from different perspectives (on both retail and wholesale markets). In order to achieve our goal we make the central assumption that the *inter-provider cost distribution model based on the determination of an original initiator of a transmission is beneficial and improves social welfare.*

In more precise terms, the research questions that are addressed can be summarized in the following points:

- How can the original initiator of an IP transmission be determined?
- How can the information about the IP transmission initiator be conveyed along the path?
- How can the proposed intercarrier compensation model be supported in a large-scale system?

1.2 Approach

The ability to perform intercarrier compensation based on the original initiator of a transmission would allow i) to reduce the existing imbalance in the allocation of the interconnection costs and ii) to promote the improvement of social welfare. To illustrate this point consider the telephony market. The developing countries are characterized by the lack of a regional communication infrastructure, which leads to a scarcity of cheap international connectivity. This results in an imbalance between incoming and outgoing traffic in developing countries, which is explained by a different level of affordability in different countries. Consequently, the revenue obtained by an operator located in a developing country mostly comes from incoming calls.

In contrast, international Internet interconnection is based on transit arrangements, where the customer provider pays for the entire traffic flow. Although it may be argued that a TCP session can be considered as a call where the initiator of a session pays for the entire traffic flow, such a model deals with technical issues, considerable costs, and implies uniform retail pricing [46], [49]. To satisfy the simplicity criterion that is crucial in the Internet we follow an *Internet interconnection accounting model that is packet based*. In order to diminish inequality in the interconnection cost allocation, each provider has to be compensated when its infrastructure is used by others. As discussed earlier, traffic flows provide a poor basis for cost sharing, since it is impossible to determine who originally initiated any IP transmission. Therefore, we suggest that *providers compensate each other based on the original initiator of a transmission*, who is determined by means of traffic differentiation into two types. In the proposed model, providers get compensated differently for traffic originally initiated by their own customers, as opposed to traffic initiated by customers of other networks. Unlike the PSTN model, where the transmission initiator covers the entire costs, imposing uniform retail pricing, our model stimulates cost sharing between all parties and supports the diversity of the existing retail pricing schemes in the Internet. Summarizing, the proposed approach uses packet-based accounting and introduces a new cost sharing characteristic, viz., *transmission initiator*. It promotes development of infrastructures, in particular in developing countries, by reducing international connectivity costs there.

1.3 Contributions

The main contribution of this dissertation is to *provide the first intercarrier compensation scheme that performs inter-provider cost distribution in IP networks based on an original initiator of a transmission*. The main objective of the proposed solution is to ensure that each provider is compensated for utilization of its infrastructure. The key ideas that allow us to achieve this goal are:

- Determine the original initiator of a transmission by means of traffic differentiation into two types.
- Compensate interconnection costs based on the distinguished traffic flows.

The following points summarize the main components of our solution:

- A novel *Differentiated Traffic-based Interconnection Agreement (DTIA)* model and its traffic management mechanism for private peering arrangements are proposed [17]. In comparison to the existing solution, which performs cost compensation based on traffic flow, in the proposed approach, intercarrier compensation is done based on a new element, namely the transmission initiator. A critical challenge in DTIA is determining the original initiator of a transmission in packet-switched networks. We have tackled this challenge by marking the information about the transmission initiator in the IP packet header, and have proposed a simple traffic differentiation mechanism that allows accounting the volume of a particular traffic type, ignoring the detailed examination of the packet header. This makes mechanism simple and leads to low computational complexity.
- Economic models and their analytical studies are formulated to explore the impact of the determination of a transmission initiator on the wholesale and retail markets [18], [20], [21], [24]. More specifically, the studies examine inter-provider payments, demand, and profits of providers dealing with all available market states in terms of providers' market shares. The economic models consider reciprocal and non-reciprocal access charges.
- The DTIA model and its traffic management mechanism are extended for transit arrangements [23]. This mechanism considers important properties, such as simplicity and *scalability* for deployment in the Internet. To convey information about the traffic type along the path, our mechanism requires a two-bit value incorporated in the IP packet header. The simple packet re-marking operations allow the recognition of the traffic type with regard to the interconnected networks. Further, we have addressed the issue of incentive compatibility (i.e., how to ensure that it is in the best interest of a provider to mark packets truthfully). More specifically, if a provider marks a packet mendaciously, it bears financial loss.
- Economic models and their analytical studies are provided to investigate a key question; that is how attractive traffic differentiation is to all participants of the

communications market [22], [25]. More specifically, our analysis examined the customer providers only and then providers of different layers. Finally, the studies explored economic efficiency of the market that improves social welfare.

1.4 Thesis Overview

The rest of this dissertation is structured as follows. Chapter 2 discusses fundamental concepts and a literature review related to this thesis. In the first part, network technologies such as circuit switching and packet switching are discussed. In particular, the features of these networks and their differences in interconnection economics are summarized. In the second part, it examines international Internet interconnection challenges and the proposed solutions.

Chapter 3 proposes a novel intercarrier compensation model, referred to as DTIA *for private peering arrangements* to overcome the existing imbalance in the allocation of the interconnection costs. This solution is the first to distribute inter-provider costs based on the determination of an original initiator of a transmission. The chapter presents a traffic management mechanism that supports the proposed approach. It formulates economic models and provides analytical studies to evaluate the strategy on the wholesale and retail levels of the market. The solution is compared with existing models.

Chapter 4 extends the model presented in Chapter 3 *for transit arrangements*. In the first part, it designs a traffic management mechanism with the defined functionalities that satisfy scalability issues. Moreover, it discusses the issue of incentive compatibility (i.e. how to make it rational for the providers to mark packets truthfully) of the proposed mechanism. In the second part, analytical studies are provided to evaluate the effectiveness of the presented approach from the perspectives of different players. It also investigates the effect of traffic differentiation on social welfare of a system.

Chapter 5 summarizes the conclusions of this dissertation and discusses the directions for potential future work.

Chapter 2

Fundamental Concepts and Related Literature

"Sometimes one pays most for the things one gets for nothing."

Albert Einstein

This chapter provides an overview of the fundamental concepts and research work relevant to this thesis. In particular, it introduces methodologies of telecommunications and surveys the state of the art in the Internet interconnection challenges.

2.1 Interconnection in Telecommunications

Information and Communication Technologies (ICTs) are an inherent part of human society. A user subscribed to a communications network enjoys the benefits of information exchange with others. The ICTs do not operate isolated from each other, instead, they cooperate with one another. Interconnection is important for the convergence of various networks and their integration into a whole [63]. *Interconnection* refers to the physical and logical linking between different communication networks so that a user of one network can communicate with the customers of another network and also access the services present in another network. According to the International Telecommunication Union (ITU) the term *interconnection* is defined as

"The commercial and technical arrangements under which service providers connect their equipment, networks and services to enable customers to have access to the customers, services and networks of other service providers."

In the beginning, technical standards, service definitions, and interconnection contracts were relatively simple. However, demand to access the Internet, which nowadays represents a powerful tool to information and knowledge, is increasing. Due to the continuous development of the telecommunication infrastructure and associated electronic commerce, new interconnection policies[1] are required to provide a more competitive environment. In other words, economic research is focused on the efficient provision of the network services and proper allocation of the costs [71].

The migration to the IP-based Next Generation Networks (NGNs) represents convergence of the traditional telephony and the Internet. Internet interconnection fundamentally differs from interconnection of the traditional telecommunications networks, based on circuit switching. More specifically, unlike the Internet, the telephone industry is highly regulated. The imposition of regulation generally is appropriate to protect anti-competitive behavior of communications networks with market power against smaller providers in a variety of ways. The industry-specific regulations are rules or restrictions applied by a legitimate authority that governs the activities of the operators. To ensure the efficiency of the entire system, the emergence of NGNs poses challenges in establishing the prices for interconnection. Interconnection pricing is a key regulatory issue, and is crucial for the development of competition.

The remainder of this chapter is organized as follows. Section 2.2 discusses the fundamental differences between the telephony model and the Internet in order to explain the interconnection economics of these networks. The existing cost distribution models in the telecommunications networks are described in Section 2.3. The difference between interconnection in the telephone industry and the Internet is covered in Section 2.4. Section 2.5 examines the international Internet interconnection issues. And finally, Section 2.6 concludes this chapter by summarizing our findings.

2.2 Circuit Switching vs. Packet Switching

This section proceeds by considering the fundamental differences between circuit-switched and packet-switched networks. In the Public Switched Telephone Network (PSTN) each circuit (channel) is dedicated to a particular connection, and therefore, traffic flows in both directions along a symmetric path. An active channel is unavailable to other users, no matter whether actual communication takes place or not. In IP networks, data is divided into chunks, called *packets*, which are sent towards the destination through a shared network. For routing an individual packet and its delivery to a destination host, the IP protocol is used over the network. In order to identify a host, it is assigned at

[1]Policy is the key determinant of legislation and regulation [63].

least one IP address. The current addressing system, called IPv4, uses a 32-bit number. However, due to the dynamic growth of the Internet, the next generation protocol (IPv6) uses a 128-bit number for the IP address. Once arriving at the destination, the packets are reassembled to restore the original information. The major advantage of packet switching is *statistical multiplexing*, i.e., sharing of the communication channel. Therefore, in contrast to the telephony approach, in the Internet the packets are routed irrespective of each other. Statistical multiplexing provides higher link utilization than the circuit switching technology, however, on the other side, can lead to congestion. This happens when the volume of traffic exceeds the network capacity. Consequently, circuit switching provides more reliable connections, than a packet switching network, which works in a best-effort manner.

Apart from technical differences between packet-switched and circuit-switched networks, there also exist differences on the business side, which influences the structure of these networks. Before examining financial models which determine the cost distribution between networks, we consider "transaction unit" in telephony and the Internet. Consider a scenario where Alice makes a call to Bob. Accepting the call, Bob incurs termination costs to its provider that should be covered either directly by billing Bob or indirectly by billing the calling party's carrier. As cited in [26], "existing access charge rules and the majority of existing reciprocal compensation agreements require the calling party's carrier, [...], to compensate the called party's carrier for terminating the call". Thus, the initiator of the call, i.e., Alice pays to the subscribed provider for the entire call since Alice asked to reserve the circuit. In contrast to the telephony example, establishing a connection in the Internet does not require the reservation of a circuit. Therefore, as cited in [75], "it is very important to distinguish between the *initiator* and the *sender*, and likewise between the *destination* and the *receiver*". The initiator is the party that initiates a call or a session, and the destination is the party that receives a call. In contrast, the sender (the originator) is the party that sends traffic, and the receiver (the terminator) is the party that receives traffic. In the telephony, the initiator is considered to be the originator, and is charged based on the transaction unit, namely a "call minute" for using the terminating network.

Huston in [46], [49] examined *two potential settlement models for the Internet, which are based on the packet cost and Transmission Control Protocol (TCP) session accounting.* The *packed-based settlement model* accounts each packet transferred through the network, under which either "sender pays" or "receiver pays" retail pricing can be used by Internet service providers (ISPs). If the first retail pricing is used, then the *originating* network pays the interconnection fees to the *terminating* network to deliver traffic. If the "receiver pays" model is applied, then the *receiving* network funds the *sending* network for a received packet.

In the strawman model where each network sells a packet to an adjacent network, the total cost of carrying a packet increases. Consequently, a network benefits when it successfully delivers (i.e., sells) a packet to the next ISP. This creates a motivation to improve the quality of a network since there is no economic incentive to drop a packet, implying financial loss. As explained in [46] the packet cost accounting model "does allow for some level of reasonable stability and cost distribution in the inter-provider settlement environment".

The following shortcomings are associated with this mechanism. Providers should maintain complete routing tables in order to minimize the liability from accepting undeliverable packets, and accept only packets with reliable routes. Moreover, there is an incentive to abuse this mechanism by sending malicious packets through a provider interface, in order to gain revenue. However, the major weakness of this model is varying retail prices, which are based on incremental per-hop transmission costs. More specifically, consumers do not want to deal with variable pricing schemes, which are difficult to understand [19].

A TCP session can be the basis of an alternative accounting model where the initiator of a session pays for the entire traffic flow. However, deployment of such mechanisms experience technical issues and considerable costs. More specifically, the provider has to maintain a complex identification process of a transmission initiator, and has to inspect the IP header of packets in order to determine and record all subsequent packets of a transmission. Moreover, as mentioned in [46], the biggest disadvantage of this model is the diversity of the existing retail pricing schemes, such as flat-rate, received or sent volume-based, mixed, etc. The TCP session model implies uniform retail pricing (i.e., the initiator of a session is charged) and therefore, does not match the real Internet environment.

Continuing the example above, Alice, the initiator of a call under the TCP model, will pay for the entire traffic flow. If we are concerned with the actual use of network resources, the financial settlement needs to be done at the IP level, accounting each packet of a flow. In this case the sender can be charged for an originated packet. Currently the Internet uses the *packet-based accounting model*, under which the volume of the exchange traffic in both directions is measured, and adopts a small set of interconnection models. More specifically, in the *service-provider* (unilateral) settlement, namely *transit and paid peering business relationships*, a customer ISP pays to a transit ISP for sent and received traffic. In the *settlement-free* agreement, namely *peering relationships*, providers do not pay each other. The alternative to peering and service-provider settlements is the *negotiated-financial* (bilateral) settlement where the payments are based on the net flow of traffic. However, which direction money should flow in relationship to traffic flow

Characteristic	**Circuit Switching**	**Packet Switching**
Provided Service	Single Service: human conversation	Multi-service
Transaction Unit	Call	Packet
Service Reliability	Guaranteed	No guarantee: best-effort packet delivery
Network Path	Symmetric for forward and reverse traffic flows	Asymmetric for forward and reverse traffic flows

Table 2.1: Fundamental Differences between Circuit Switching and Packet Switching.

is not immediately obvious. Therefore, this model introduces significant financial risks to the ISP interconnection environment and is not a commonly deployed mechanism. For detailed discussion see [46], [49], [41], [75]. The fundamental differences between the telephony model and the Internet model are summarized in Table 2.1.

2.3 Economics of Network Interconnection

The interconnection of telecommunications networks have been extensively studied in the literature (see the seminal papers [3], [56]). Various interconnection models between symmetric and asymmetric networks are introduced in [11], [12], [13], [45], [72], [73]. The survey of existing studies of interconnection has been reviewed in [57], [4]. This section discusses the economics of interconnection, providing an overview of the existing financial models in the telephony and the Internet at the wholesale level.

It is known that usually, before interconnecting, each provider calculates whether the benefits would exceed the interconnection costs [57]. The simple economic principle suggests sharing the costs between all parties. For example, in telephony it was argued that both calling and called parties benefit from the call, and consequently, should share the interconnection costs [26]. In order to determine the distribution of the interconnection costs, providers arrange interconnection models [46], [41]. The two standardized types of Internet interconnection agreements are peering and transit. Being able to communicate with anyone in the Internet increases the benefits of the system and thereby provides *strong positive network externalities* as defined in the economics literature and as explained below.

2.3.1 Network Externalities

In economics, an *externality* is an impact of one party on someone else who is not directly involved in an activity (transaction) [31], [32]. In the system without externalities, costs should be shared based on the benefits obtained by each party. However, like any other network, the Internet exhibits externalities, and therefore, it is impossible to measure the total benefits of parties and so to share the costs in a fair way. The Internet exhibits two types of externalities, *positive* and *negative*. The network *positive externalities* emerge when the utility (benefit) derived from consumption of a service increases as more customers use it (i.e., with the increase in the size of a network). The reason of this effect is the *complementary relationship* among the components of the system. In particular, when joining a network, a user considers only the private benefits and does not take into account that the value of the entire network increases with its size. The impact when someone imposes the costs on other participants without suffering penalty is defined as *negative externalities*. Congestion is an example of negative network externality.

The literature also considers *direct* and *indirect* network externalities. The externalities can be direct when users communicate with each other or share files. In this case the more subscribed users exist, the higher the value of a network for each user. A classical example of a network that exhibits direct externalities is the telephone system. Indirect network externalities exist when the growth in network size increases the number of services available to the users of a network: the more subscribers are in the Internet, the more content will be provided. Generally, the Internet externalities are associated with a statement known as "Metcalfe's Law", which claims that the value of a network is proportional to the square of the number of users connected to it.

2.3.2 Interconnection Arrangements for Telephony

Before considering the business models for the Internet, we examine interconnection arrangements within the international telephony model. There are essentially three possible interconnection relationships for circuit-switched networks, such as *Bill-and-Keep (BAK, also known as the Sender Keeps All, or SKA), Calling Party's Network Pays (CPNP), and a model with unilateral transit fees* [49]. Under the *BAK arrangement* the calling party's carrier does not pay any termination charge to the called party's carrier. More specifically, each network agrees to terminate the calls from the other network at no charge and recovers the termination costs from their own customers. The retail prices that reflect the network usage costs and the other commercial considerations eventually lead to competition among carriers. The BAK model exists only under the restrictive condition of roughly balanced traffic flows in both directions. The lack of termination fees can "cause originating carriers (and calling parties) to overuse other carriers' termination facilities" [39]. Therefore, BAK arrangements are generally considered inefficient in terms of costs compensation.

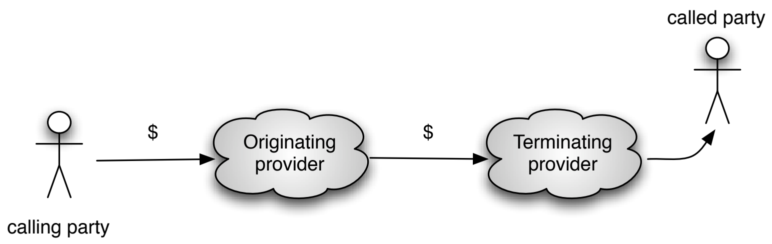


FIGURE 2.1: Calling Party's Network Pays.

Unlike BAK, the *CPNP arrangement* assumes that the subscribers do not pay for the incoming calls. Instead, both providers charge each other a common call accounting rate to compensate the interconnection costs. In CPNP, the calling party's Local Exchange Carrier (LEC) or Inter-exchange Carrier (IXC) pays the called party's local network for the call transfer through its network. More specifically, the calling subscriber pays an originating fee, called *access charge*, to the calling party's LEC, and a terminating access charge to the called party's LEC, i.e., covers the entire call. The structure is shown in Figure 2.1. Access charges can be either *flat-rate*, meaning that a user is charged a monthly subscription regardless of usage and actual network conditions, or *usage-based* under which a user is charged on a per-minute basis.

An important issue addresses the question of what network costs should be recovered by access charges. Generally, the costs of a network are categorized as *traffic sensitive* and *non-traffic sensitive* costs. Traffic sensitive costs vary with usage, while non-traffic costs (local loop equivalent) do not vary with usage and constitute the most of the cost of interconnection. According to economics the costs should be recovered in a manner they are incurred [70], [40]. Therefore, traffic sensitive costs should be recovered through a usage-based price, and non-traffic sensitive costs should be recovered through a flat-rate price. In particular, it was shown that an economically efficient access charge should be equal to the marginal cost[2] of access. There has been debate on traffic sensitive and non-traffic sensitive costs. Traditionally, the non-traffic sensitive cost has been split between long-distance carriers and a customer in order to keep the subscriber's monthly fee low. However, usage-based prices, which recover the fixed costs, diminish social welfare by causing users to buy fewer services [34]. Recently, Federal Communications Commission (FCC) recommended reforming the existing distribution of the access charges, which cannot be sustained in a competitive environment [39]. The series of the FCC's actions on changing the structure of access charges in telephony lead to the decrease of long-distance access charges, and consequently, the enhancement of consumer welfare.

Some pressing issues arise from the CPNP model. First, the major problem of this arrangement is that the terminating carrier, irrespective to its size, has a *monopoly*

[2]Marginal cost is the costs required to produce an addition unit of output.

power over termination to its customers [39], [61]. In other words, only a single provider can terminate calls to a particular telephone number. Especially in case of long distance, there are a number of competing IXCs that can transfer a call between LECs of both parties, but a call should be transferred through the IXC of the terminating carrier. Consequently, in the presence of a termination monopoly, the provider can increase the termination charges without loosing the customers. In fact, due to a growth of the average termination price, the users have little or no incentive to change the operator [15]. To prevent a monopoly in the market, it is necessary to impose regulation of termination rates.

A special case of the CPNP model is when the intercarrier compensation for long distance is governed by designed access charges applied in one direction. In this model with *unilateral transit fees*, one party, namely the *transit provider* charges the customer provider for originating and terminating traffic.

In some cases, providers serving complementary markets use the *revenue sharing arrangement* (RSA) as a substitute for paying explicit interconnection charges. The RSA model is based on a negotiation between providers and, generally, is unrelated to the actual costs of the networks. As a result, efficiency of such an arrangement depends on how precisely networks access their costs.

2.3.3 Internet Interconnection

History of the Internet Interconnection

Let us briefly discuss the evolution of the Internet and its architecture [14]. Prior the commercialization of the Internet, in 1969, there was only one backbone, ARPANET, funded by Advanced Research Projects Agency (ARPA) of the U.S. Department of Defense. One of the research programs of ARPA was to investigate large-scale systems in order to allow collaboration between scientists and researchers. Thus, ARPANET was the first packet-switched network which allowed exchanging information between connected computers. In 1985, National Science Foundation (NSF) funded the NSFNET backbone project, which connected five supercomputer centers. As the demand for the Internet access grew, the number of the commercial networks began to increase. However, according to the Acceptable Use Policy (AUP) it was not allowed to exchange commercial traffic over the NSFNET backbone. As a result, in the beginning of the 1990s, commercial backbones established Commercial Internet Exchange (CIX) to interconnect and directly exchange the traffic of their own users. In 1995, NSFNET was transitioned to the private sector, by interconnecting commercial ISPs at four geographically distributed Network Access Point (NAP), which were privately owned and operated by Sprint (in New York), Pacific Bell (in San Francisco), Ameritech (in Chicago), and MFS (in Washington D.C.). Thus, NAPs were the first commercial Internet Exchange Points (IXPs) where backbones could choose any NAP to interconnect with one another. A NAP provider was obliged to provide and operate switching facilities under the conditions defined by NSF.

Internet Architecture and Infrastructure

The Internet is a system of interconnected networks, which are connected either through a direct link or through an intermediate point, called IXP to exchange traffic. The autonomous systems (ASs) which comprise the Internet, communicate with each other in a decentralized manner, i.e., without central authority, supporting the standardized Internet Protocol Suite (TCP/IP).

The Internet has a hierarchical structure because of existing relationships between providers, known as *horizontal* (e.g., peering) and *vertical* (transit) interconnections. A hierarchical model of the Internet connectivity market, called *tier structure*, consists of three main levels of the participants [15]: the Tier-1 that is the top of the hierarchy consists of the Internet backbone providers (IBPs), the Tier-2 consist of downstream ISPs, and the Tier-3, which is the bottom of the structure, consists of ISPs that service customers directly. Each tier is the customer of the tier above. The top tier consists of the backbone ISPs, such as AT&T, Verizon Business (MCI/WorldComp), Sprint, Cable & Wireless, and Genuity (formerly called GTE Interworking). Generally, there is no money exchange between backbones (i.e., they peer) since originated traffic volumes are symmetric and IBPs would both benefit equally. IBPs get access to the whole Internet, without purchasing transit from anyone. Instead, IBPs sell the wholesale services to the competitive ISPs. In the second tier providers operate at the national and regional levels. In order to get access to the whole Internet, they acquire transit services from the top tier backbones. And finally, the Tier-3 ISPs consists of the providers which operate on the retail market and sell connectivity services directly to the customers. Tier-3 providers arrange transit relationships with the upper tier providers to access the Internet. The Internet hierarchical structure is shown in Figure 2.2.

Historically, the Internet provides two types of interconnection arrangements: peering and transit [66]. Peering is the business relationship that usually takes place on the same level on the Internet hierarchy. In contrast, a transit relationship is hierarchical where one provider pays another to deliver the traffic between the customers. The outcome of the negotiation process of being a transit or peered ISP reflects on the assessment of the actual cost of traffic exchange and was studied in [67], [68]. Peering offers several

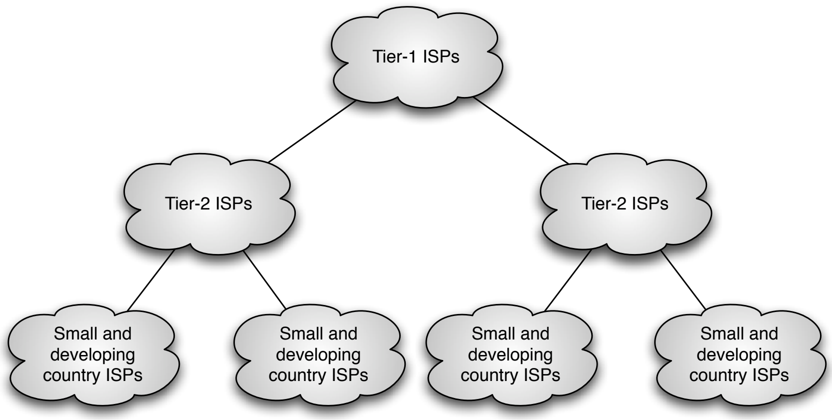


FIGURE 2.2: Internet Hierarchical Structure.

advantages in terms of interconnection costs and quality of data transmission, but gives access to a part of the entire Internet only. According to the estimates in [53], 80% of the Internet traffic is routed via private peering. In some cases, however, in order to recover the infrastructure costs, instead of peering with the smaller ISPs, the larger ISPs offer transit arrangements at a certain rate, providing access to the whole Internet. In addition to this, new types of interconnection models, such as paid peering and partial transit, have emerged in the market [38]. The following subsection discusses the Internet interconnection arrangements in details.

2.3.4 Interconnection Arrangements for the Internet

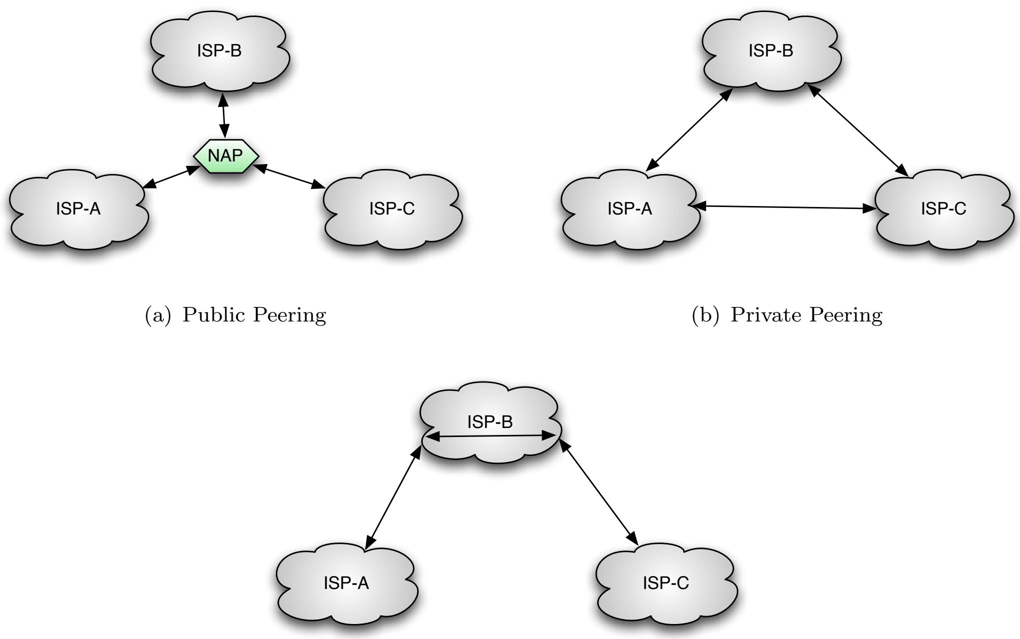
Peering is the arrangement of traffic exchange on the free-settlement basis, called Bill-and-Keep, so that ISPs do not pay each other and derive revenues from their own customers only. Peering arrangements do not specify any minimum performance of traffic, which is handled in a best-effort manner. Peers exchange traffic only between their own customers and do not act as intermediate or transit carriers. It is fair and efficient under symmetry of traffic flows, termination charges, and costs. To ensure balanced traffic flows, generally, providers of similar size will peer with each other. The measures of a network size could be several criteria, such as the number of subscribed customers, geographical coverage, traffic volume, network capacity, or the number of content websites. In order to establish peering, only set up costs are shared, so that each ISP pays for its own equipment and circuit. Routing information is exchanged and updated between peering parties using the Border Gateway Protocol (BGP). Peering can be differentiated based on three different criteria [74]. Firstly, according to the physical interconnection, peering can be categorized into the following two types: *public* and *private* peering. *Public peering* allows interconnecting many parties via a peering fabric, at a focal point, called NAP, or IXP, as shown in Figure 2.3(a). Because of the rapid growth of the Internet traffic IXPs eventually became congested [1]. In order to avoid bottlenecks at IXPs and to improve data transmission quality, providers began to interconnect directly with each other based on *private peering arrangements*, as indicated in Figure 2.3(b). Private peering offers dedicated capacity that is not shared with the other parties. However, a fully interconnected structure consisting of N providers requires $N * (N - 1)/2$ interconnections, and therefore, leads to scalability issues in large-scale systems. Discussions on the evolution of peering arrangements were provided by several researches [8], [52].

According to the second criterion peering with respect to the number of peering partners is divided into two types, such as *bilateral* (BLPA) and *multilateral* (MLPA) peering agreements. On the BLPA basis, ISPs exchange traffic destined for each other's customers. In MLPA, more than two ISPs are involved, and in some instances, fees are charged for the traffic exchange. Financial compensation is significant to cover transmission costs when traffic is unbalanced. And finally, peering is differentiated according to the market it deals with: *primary* peering in the top tier market or *secondary* peering in the downstream market. Peering itself reduces transit costs, which ISPs pay for connectivity to the global Internet. Moreover, direct interconnection reduces latency by avoiding packet transmission over great distance. In general, the ISP's decision on whether to peer depends on an estimation of costs for setting up a peering, and savings which it can make without connecting to a transit provider [66], [42], [69]. Various aspects of peering arrangements have been analyzed in [55], [28], [29], [7], [59], [54], [65].

Unlike peering, in the *transit model*, a customer provider (downstream ISP) pays a transit provider (upstream ISP) to deliver the traffic between customers, and therefore, incurs the total interconnection costs. The structure is indicated in Figure 2.3(c). More specifically, a customer ISP pays for a port into the transit network and for the capacity of a link. Thus, in case of international connectivity, the costs are not shared, and a downstream ISP pays for the both ends of the international lines and the costs of the exchanged traffic (even through traffic flows in both directions). Generally, the total payment amount depends on the exchanged traffic volume since transit fees are typically offered on a megabit per second per month basis (Mbit/s/Month). A transit provider using BGP advertises the preferred routes of its peering and transit partners. Interconnected providers negotiate an agreement, called Service Level Agreement (SLA), which specifies the required level of transit services provided to a customer ISP. SLAs are generally not disclosed.

Due to the dynamic nature of the Internet new types of providers, such as *content* networks and *eyeball* networks, emerged in the markets [38]. Two types of content providers are considered: content providers like Abovenet and Cogent host a great amount of content; and large content providers such as Google and Yahoo. The large providers (Google and Yahoo) are interacting with the eyeball providers like Verizon and Comcast which host a large number of the subscribed users. The content and eyeball providers cause highly asymmetric traffic flows: indeed, traffic generated in response to a user request is much more compared to the traffic submitting this request. As a consequence, the new types of providers led to the emergence of the new types of interconnection arrangements, such as *paid peering* and *partial transit*. In a paid peering arrangement, providers advertise route information of their own customers, however, unlike in the peering model, traffic is exchanged on a settlement basis. This model can take place when a provider does not need access to the whole Internet, and can safe money without purchasing transit services. Under a partial transit arrangement, a network announces a particular subset of a routing table to its customer provider at a discounted price from the full transit. The providers seek to obtain this commitment primarily for two reasons: to balance inbound and outbound traffic, and to give their customers access to the valuable peering relationships. Discussion on the diversity of the Internet interconnection models that exist today can be found in [38].

Comparing the intercarrier compensation models in PSTN and the Internet, it is worth



(a) Public Peering (b) Private Peering

(c) Transit

FIGURE 2.3: Interconnection Arrangements for the Internet.

noting that the bilateral settlement model of telephone networks, namely CPNP, is not applicable in the Internet. The principle reason is the significant difference between the Internet and telephone infrastructures: unlike PSTN that is circuit-based and connection-oriented, the Internet is packet-based and connectionless.

2.4 Interconnection and Regulation

The telecommunications industry takes advantage of *economies of scale* which arise when cost per unit decreases as the volume of production increases. For example, Internet access in the USA is cheaper than in some other countries because of the developed infrastructure both in terms of number of users and amount of content [63]. According to economic theory and practice a *monopoly is likely to appear in the industry with the presence of economies of scale*. Indeed, telecommunications operators generally have high fixed costs, and therefore, it is easier for one company to expand than for another to enter the market. The monopoly implies artificially increased service prices above the competitive level and/or degradation in quality of service (QoS). Moreover, natural monopolists are likely to leverage and abuse their market power. The existence of a transparent and competitive market is crucial for the fair distribution of the interconnection costs. Crémer stated that there are three ways to achieve network connectivity: "regulation, private negotiation among providers, and alternative methods, such as the customer's affiliation to multiple networks" [16].

Generally, in order to open the market for competition and to ensure affordable access to the network, governments regulate the natural monopolists in the market. In 1934, Congress established FCC to regulate telecommunications common carriers and thus prevent unreasonable discrimination [52]. The telephone industry is regulated domestically and internationally. Unlike the telephony, the Internet interconnection is decentralized and is not subject to any industry-specific regulations. The Internet interconnection is based on bilateral negotiations, and its outcome is described by the well-known Coase theorem introduced by the British economist. The Nobel Prize laureate Ronald H. Coase stated that in the presence of a competitive market private negotiations between parties could lead to a more efficient outcome than regulation handled by government. Since it is unlikely that the backbones are able to gain significant market power in order to act in an anti-competitive manner, therefore, bilateral negotiation is a reasonable solution for the Internet environment [62].

The Unregulated Internet

This section briefly discusses why the Internet is unregulated and when the regulation may be imposed as in the telephone industry. According to [52], over forty years, "the absence of market power in the computer services industry led the Commission to conclude that imposing common carrier regulation was unnecessary and might discourage innovation and distort the nascent data marketplace". The influence of deregulation in the development of the Internet is highlighted in the 1996 Act that states "the Internet ... [has] flourished, to the benefit of all Americans, with a minimum of government regulation." [52]. Over the last years the Internet increased drastically in size. The analysis showed that since the Internet privatization in 1995, the market for Internet backbone services has expanded, and in 1999 consisted of forty-two national backbones [52]. However, it was questioned whether larger backbones are able to exercise market power against smaller and new backbone providers. The study [52] examined the possible anti-competitive behavior of the backbones, considering both the competitive and dominant backbone markets.

In the *competitive market*, the Internet backbone providers have an incentive to cooperate with each other while competing for the retail and wholesale customers. There is concern that backbone providers discriminate the smaller providers, refusing to peer with them. This action was stated as anti-competitive. However, the anti-competitive behavior addresses the actions that harm consumers but not the competitors. The major index of market competitiveness is whether new affiliates can enter the market successfully. In the competitive backbone market there are two reasons that connectivity services are available in a nondiscriminatory manner. First, the larger backbones can refuse to peer with smaller ISPs for legitimate reasons, such as free riding, under which the infrastructure investments are not compensated, etc, but because of competition in the top-tier market, have an incentive to offer transit interconnections. And second, backbones competing for the transit business have no incentive to use a price squeeze and therefore, set the prices for acquiring the interconnection services at the competitive level.

In the market with a *single dominant backbone*, anti-competitive actions indeed could appear. Although it is unlikely that provider can grow and become a dominant backbone, such dominance could be achieved for example, by consolidation [52]. Existence of a dominant backbone, like in the case of a natural monopoly, could harm public interests in some ways. In particular, a dominant provider i) can raise retail prices, ii) can use market power by denying access to its network, i.e., refusing to interconnect with smaller providers, and finally, iii) can raise the prices at the wholesale market. In addition to this, a dominant provider can also apply *non-price-based discrimination*, such as degradation in quality of interconnection in order to "steal" customers of a rival provider. The study [52] examined an anti-competitive manner of a dominant backbone, and argued that until there are competitive backbones in the market no need for regulation is required.

It is acceptable that providers are unable to obtain sufficient market power to act in an anti-competitive manner, however, this assumption may not be viable in the system of universal connectivity between backbones [52]. For the purpose of attracting new users or increasing revenues, backbones differentiate and offer new types of services to their customers. Some pressing issues arise from the possible Internet *"balkanization"* where competing providers attempt to differentiate themselves from others. In particular, some backbones may not have an incentive to interconnect with others in order to share a particular service. Such a decision might be based on the fact that other backbones are not able to guarantee a certain level of quality of the provisioned services. Another issue concerns the possible increase in congestion level. Since there is no money exchange in the peering model, providers have little or no economic incentive to increase their capacity to terminate traffic. This may lead to a degradation in the level of QoS. Under such circumstances, a provider who is unwilling to interconnect can grow and become dominant. To prevent harming public interest, i.e., social welfare, industry-specific regulations might be applied. However, the study [52] showed that even at the first stage providers are unwilling to interconnect, this is a temporary phase. More specifically, imposition of regulation is unlikely to be necessary because there are strong market forces that would induce providers to interconnect.

2.5 Interconnection Challenges

This section discusses international Internet interconnection issues and the proposed recommendations. It also examines international connectivity to the Internet in a converging environment.

2.5.1 International Internet Interconnection

For many year international interconnection has been the subject of debate related to the cost of connectivity to the Internet. In recent years, some non-U.S. carriers, especially from the Asia-Pacific region, complained about unfair sharing of the international transmission capacity costs. Non-U.S. carriers arranging transit relationships with U.S. carriers are required to pay the full costs of international Internet connectivity regardless of the direction of traffic flows.

The recent study reported by the Telecommunication Working Group set up by Asia-Pacific Economic Cooperation (APEC) stated that the traffic to and from the U.S. became more balanced. In fact, the Australian carrier Telstra claimed that 30% of the traffic between Australia and the United States is flowing from Australia to the U.S., due to increasing demand for the content provided by Australia [52]. Further, Telstra argued that it subsidizes the U.S. carriers whose customers are utilizing its infrastructure.

On the other side, according to the European Commission report, the European backbone providers stated that international connectivity is evolving rapidly and leads to "many different types of arrangements for achieving global connectivity" [35]. In particular, some local European providers arrange peering with transit ISPs and therefore, access the U.S. backbones without payment. Indeed, according to all publicly available information, there is no indication that any U.S. backbones are abusing market power with respect to non-U.S. carriers.

Since 1998, the ITU has studied the issue of international interconnection cost sharing. In particular, this issue was raised on the debate, known as International Charging Arrangements for Internet Services (ICAIS). Later in 2000, the ITU adopted the recommendation D.50 that pursued to encourage providers to adopt symmetric peering arrangements [51]. However, this failed due to various FCC studies, which demonstrated that symmetric peering is lacking, and that commercial agreements are dominant. As a result, recommendation D.50 admitted commercial arrangements suggesting that providers take into account "the possible need for compensation between them for the value of elements such as traffic flow, number of routes, geographical coverage and cost of international transmission among others" [58].

In 2000, the Sector ITU-T/SG3 adopted a proposal, introduced by the Asia and Oceania Region tariff group, which recommended the establishment of bilateral arrangements and the compensation of each provider for the costs that it incurs in carrying traffic generated by the other provider. In response to this, the USA submitted to the ITU World Telecommunications Standardization Assembly (WTSA) "formal contributions in opposition to both the substance of this recommendation and the procedures used in its adoption" [52]. In fact, traffic flows are not a reasonable indicator to share the costs since it is not clear who originally initiated a transmission and, therefore, who should pay for the costs. More specifically, an incoming packet to Taiwan from the USA, may be i) either part of a transmission, such as webpage that was requested by user in Taiwan or ii) part of a transmission, such as an email that was sent by a customer in the USA. Moreover, in some cases, U.S. backbones accept traffic from one Asia-Pacific region that is forwarded to another Asia-Pacific region. In such cases, the U.S. customers do not benefit from this traffic. Overall, it can be concluded that compensation between providers cannot be solely done based on the traffic flows, which provide a poor basis for cost sharing. The current program of the ITU-T Study Group 3 for the Study Period 2009-2012 continues to study international Internet connectivity aspects meeting the standardization challenges.

The issue of unequal cost distribution between networks makes the access and the use of the Internet more expensive for customers, especially in low-income developing countries [35]. Interconnection challenges in developing countries have been extensively studied [10], [30], [58], [43]. In particular, a report provided by African Internet Service Providers Association (AFRISPA) is concerned with the net cash that flows from the developing South to the developed North. Being a key element in telecommunications, interconnection "is needed to achieve equitable and sustainable expansion of infrastructure services in the poorest countries of the world" [10]. African backbone providers pay for the access circuits, and therefore subsidize the connectivity costs to the international backbone providers. For example, when a Kenyan user sends email to the USA, it is the Kenyan ISP that bears the cost of the international connectivity from Kenya to the USA. When a user in U.S. sends email to a user in Kenya, it is still the Kenyan ISP that bears the cost of the international connectivity [63]. Such a cost distribution leads to higher subscription fees in Kenya. It was estimated that annual connectivity costs by Asia Pacific ISPs reach a total of USD 5 billion, and the costs by African operators come to between USD 250 and USD 500 million [10]. The scarcity of cheap international connections and the degradation in quality of service is caused by a variety of reasons, such as geographical remoteness, the lack of regional/international communications infrastructure and competition in developing countries. The lack of regional and national transmission infrastructures in Africa imply that a considerable amount of traffic goes via Europe or North America. This adds additional costs to the operations of the providers, and therefore makes international interconnection costly. As cited in [63] the gap between Internet access in developed and developing countries is huge and continues to increase. In particular, only 5% of the people in low-income countries, which make 60% of the world's population, have access to the Internet.

2.5.2 Next Generation Networks

Migration to the NGNs, which implies a combination of the Internet and the traditional telephony system, enhances the urgency to resolve international interconnection issues [58]. More specifically, the costs of interconnection borne by developing countries are expected to increase as more traffic migrates to NGNs. The ITU estimated that during the period between 1993 and 1998, the net payments from developed to developing countries for international telephone calls reach a total of USD 40 billion. However, due to the development of cheap technologies for voice communications (e.g., VoIP), which bypass international accounting rate system[3], the estimations of ITU-T Study Group 3 showed that now developing countries may pay USD 3 billion per year to developed countries.

The convergence of the networks raises the questions related to economics of interconnection, the possible imposition of regulation, and the degree of regulation. Indeed, the NGN interconnection problem is not a problem of technology but rather a problem of economics [60], [61]. There have been arguments to withdraw the regulation altogether since the competition progressively expands. The report [60] argued that in the long-term run this is probably the right view. However, in the short-term run (i.e., intermediate time frame) where a market has not yet become effectively competitive, regulation may be applied.

2.5.3 Interconnection Pricing

The main objective of telecommunications regulation is to promote a competitive market. The regulator prevents incumbent providers to abuse their dominant positions and ensures that there are no barriers for newcomers to enter the market [51]. Regulators can use interconnection pricing as a tool to encourage competition in all segments of a market [3], [56]. The interconnection prices are controversial because they have an impact on the competition development and profitability: while high interconnection rates are attractive to the incumbent providers and discourage entrants, low rates are thought to favour entrants, decreasing the revenues of the incumbent providers. The purpose of regulation of the interconnection prices is thus to promote the establishment of a viable and fair competition.

Generally, regulators consider four main *interconnection pricing* schemes: historical cost-based pricing, Long-run Incremental Cost (LRIC) pricing, Efficient Component Pricing Rule (ECPR), and Bill and Keep. The range of existing solutions to interconnection pricing is described in [64]. These approaches do not achieve the two objectives of interconnection pricing, viz., competition development and profitability simultaneously. Hence, no single model has a clear advantage over the others. For example, LRIC stimulates competition by encouraging new entrants in the downstream market. However, this is only achieved under a number of unrealistic/limited circumstances, and in reality, the LRIC scheme might induce inefficiencies. The detailed analyses are provided in [4], [2], [50], [33]. Thus, setting interconnection rates in a way to encourage efficient market competition remains challenging for the regulators. Some innovative concepts for the

[3]The accounting rate system provides a set of agreed prices for interconnection of international calls. Source: www.ictregulationtoolkit.org

interconnection pricing are presented in [57]. One of the assumptions considers *reciprocal* (i.e., symmetric) and *non-reciprocal* (i.e., asymmetric) interconnection charges. *Symmetry* of interconnection prices conflicts with cost-based interconnection of the networks. In particular, competing providers have different business plans, employ different technologies, and therefore, have different cost structures. *Asymmetry* of interconnection prices can have a distorting effect on the market competition. In particular, high cost networks with low market share can set higher access charges, which may diminish market development. However, asymmetric interconnection charges have been considered as increasing the sustainability of high-cost area providers and therefore, have become economically acceptable [10]. In fact, termination rates provide an opportunity to increase of revenue in low density (high-cost) areas from incoming calls. The justification for interconnection asymmetry is discussed in the following lines.

Asymmetric Interconnection Pricing

The theoretical justification for asymmetric interconnection in telephony has the following reasons [30]. Firstly, the urban networks are located in low-cost areas, while the rural networks are considered to operate in high-cost areas. This is due to the less developed infrastructure, in particular the low density of subscribed users in rural areas rather than in urban areas. Such a difference in costs explains the *higher retail prices in the rural than in urban networks.* Secondly, *setting cost-based access charges increases the economic efficiency.* It is recognized that geographical averaging maintained by the governments is considered social and desirable. However, it is also argued that the users in the *rural networks of developing countries* cannot afford high costs of services, and therefore, it is reasonable to move termination charges towards the costs. Setting asymmetric charges enhances economic efficiency in liberalized or competitive markets by increasing the interconnection revenues of the rural networks. And finally, *urban consumers are willing to pay higher prices to support rural networks*, i.e., to cover additional costs that are understandable to them. More specifically, it was shown that in spite of the rural users' willingness to pay, urban customers have more affordability and therefore, are willing to pay more to call their friends in rural networks [30]. Thus, rural networks in the developing countries with low income have the potential to increase revenue and to generate traffic [10]. In telephony, for example, it is acceptable that more than 50% of a rural network's revenue (in developing countries) could come from the incoming calls. Adoption of the asymmetric interconnection charges encourages rural networks to generate revenues not only from incoming, but also from outgoing calls.

2.6 Summary and Conclusions

In this chapter we have examined methodologies for communications networks and provided an overview of international Internet interconnection challenges. Currently, the Internet admits a small set of inter-provider cost distribution models, such as peering, transit and their variations. In particular, under symmetry of traffic flows, the termination costs are set to zero since it is assumed that the termination fees are roughly the same, and consequently, peering is negotiated. Generally, if providers are asymmetric in terms of size, the peering model is not appropriate since the providers may incur different costs and benefits. In such cases the interconnection arrangement is governed by the financial compensation in a unilaterally (paid peering, transit) or bilaterally negotiated basis to recover the costs of the network. In the bilateral settlement arrangements, the payments are done based on the net traffic flow. In the unilateral settlement arrangements, a customer provider pays for sent and received traffic, even though traffic flows in both directions. *This causes the existence of imbalance in the allocation of interconnection costs and scarcity of cheap international connectivity in the high cost areas.*

"Without the adoption of a settlement regime that supports some form of cost distribution among Internet providers, there are serious structural problems in supporting a highly diverse and well populated provider industry sector. These problems are exacerbated by the additional observation that the Internet transmission and retail markets both admit significant economies of scale of operation. The combination of these two factors leads to the economic conclusion that the Internet market is not a long term sustainable open competitive market that is capable of supporting a wide diversity of players both large and small" [49]. Summarizing, the problem of interconnection cost allocation concerns fair compensation of each provider (for utilization of its infrastructure), rather than the installation of transmission infrastructure, or the retailing of Internet services. As stated in [49] "competition is not an end in itself, nor is regulatory impost". *The objective here is to ensure an efficient and effective environment for all participants.*

The aim of this dissertation is to support the development and profitability of the communications market by reducing the existing imbalance in the allocation of the interconnection costs. The existing approaches to interconnection challenges are mainly focused on setting of interconnection charges. These models strike the balance between competition development and profitability quite differently, and therefore, no single solution has an advantage over the others. One approach towards solving interconnection issues recommended to set bilateral arrangements and to compensate each provider based on the traffic flows. However, traffic flows are regarded as a poor basis for cost sharing since it is impossible to determine who originally initiated any IP transmission. Instead of performing intercarrier compensation based on traffic flows, we suggest *to perform compensation based on the original initiator of a transmission*, where providers get compensated differently for traffic originally initiated by their own customers, as opposed to traffic initiated by customers of other networks. This approach allows to compensate providers for utilization of their infrastructures, and therefore, provides sustainable conditions for all market players.

Chapter 3

Differentiated Traffic-based Interconnection Agreement for Private Peering Arrangements

"We can't solve problems by using the same kind of thinking we used when we created them."

Albert Einstein

The objective of this chapter is to propose a novel inter-provider cost distribution model, called *Differentiated Traffic-based Interconnection Agreement (DTIA)* for private peering arrangements (i.e., between two directly interconnected providers). Interconnection of providers through transit arrangements is considered in the next chapter.

Section 3.1 discusses the key technique of our approach, which is based on the determination of the original initiator of a transmission. In order to support the proposed interconnection payment scheme, a traffic management mechanism is described in Section 3.2. For the evaluation of the proposed algorithm, Sections 3.3 and 3.4 formulate the economic models and their analytical studies. Section 3.3 presents the inelastic demand model investigating the role of the proposed approach on the intercarrier compensation. Section 3.4 considers the elastic demand model exploring the impact of traffic differentiation on both customers and providers. In particular, it studies demand and profits of the providers. The proposed model is compared with an existing solution, which performs cost compensation based on the net traffic flow. The conclusions of the studies are reported in Section 3.5.

3.1 Traffic Differentiation-based Approach

The principle that we follow is that both parties derive benefits from the exchange of traffic and should thus share the interconnection costs [6], [5], [44]. Considering a system without externalities [31], the costs should be shared based on the benefits obtained by each party. However, in the real world, which exhibits externalities, it is impossible to measure the benefits of the parties. If content is not equally distributed between providers, traffic imbalance occurs, and hence, costs and revenues are not shared evenly. Most often, traffic between peering providers is routed using so called *hot potato routing* scheme, where the sending ISP forwards packets as soon as possible and the receiving ISP incurs the majority of the transportation cost. As a result, the network that sends more traffic incurs lower cost than the network that receives more traffic [60]. As cited in [47], traffic flows are dominant towards the customers requesting the content, and they generate 85% of the Internet traffic. This implies that inbound traffic is much more compared to outbound traffic of content requests.

As discussed in Chapter 2, to avoid the existing imbalance in the distribution of the interconnection costs, there has been some pressure on regulatory commissions to adopt interconnection arrangements at zero price (i.e., peering arrangements). This model was not accepted due to inefficiency in terms of the cost compensation. One approach towards solving interconnection cost distribution issues proposed to compensate each provider for the costs which it incurs in carrying traffic based on the traffic flows. However, it was argued that traffic flows are not a good measure for costs sharing since it is impossible to determine who originally initiated any given transmission on the Internet, and therefore, provide a poor basis for cost allocation. Although it can be argued to use a TCP session as a "call", providers are unwilling to inspect the IP header of a packet since "the cost of carrying an individual packet is extremely small, and the cost of accounting for each packet may well be greater than the cost of carrying the packet across the providers" [48].

The key aspect of the DTIA model is based on the determination of the original initiator of a transmission by means of traffic differentiation into two types, referred to as *native*, which is originally initiated by the provider's own customers, and *stranger* that is originally initiated by the customers of the peered network. Indeed, outgoing traffic of ISP_i that is the same as incoming traffic of a rival provider may be either i) a part of a transmission initiated by a customer of ISP_i, or ii) a part of a transmission initiated by a customer of the peered network. Further, we suggest that a provider compensates the incurred costs differently for a particular type of traffic, where stranger traffic is charged at a lower rate than native traffic. In particular, i) fully if the exchanged traffic is native and ii) partially if the originated traffic is stranger. More specifically, interconnected networks arrange DTIA whereby each partner is compensated for the termination costs which it incurs in carrying traffic according to the differentiated traffic flows.

3.2 Traffic Management Mechanism

The traffic management mechanism for the interconnection agreements, which we propose, allows to recognize the packet type between the peered networks. The key technique of the proposed mechanism is the identification of the traffic type based on a one-bit field in the IP packet header referred to as the *Membership Label (ML)*. Incorporation of the label in the IP header is described in Section 4.1.2.

We assume that all nodes within the network support packet marking where each node sets the ML field of a native packet to '*1*' and the packet of stranger traffic to '*0*'. The assignment of the label to '*1*' is done once, when a node originally initiates a transmission. It is obvious that native traffic with regard to one network is considered to be stranger from the perspective of the other. Consequently, it is necessary to differentiate the exchanged traffic between the networks. In order to achieve this, we distinguish the provider's border nodes, which we refer to as the *Provider-to-Provider Border (PPB)* nodes. These nodes are *trust boundaries* and maintain the connection with the peered network.

For outgoing traffic, the PPB node performs the NOT logical operation on the label. In addition, in order to carry out intercarrier compensation based on the differentiated traffic flows, each PPB node keeps two counters (one for inbound and another for outbound traffic), which calculate the volume of a particular type of traffic, i.e., either native or stranger with regard to its network. The volume of the other type of traffic, e.g., native (stranger) can be easily determined by subtracting the volume of stranger (native) traffic from the total count. It is worth noting that the PPB nodes read the labels of incoming traffic (to increase counter if necessary), but do not re-examine them.

Now, a website requested by a consumer can be hosted either by the local network or by the peered network. As a result, traffic originated by the endpoint of a transmission can be part of the transmission originally initiated either by the network's customer or by the customer of the peered network. Therefore, the identification of the type of traffic (i.e., native or stranger) originated by the transmission endpoint is necessary. For this purpose, the transmission endpoint does not re-examine the label and simply sends response packets with the same ML field (i.e., the value '*0*' or '*1*' is duplicated from the request packet). It is obvious that incoming network traffic with the bit set to' *1*' is part of a transmission initiated by its own customers. An example that helps to understand how the described traffic management mechanism works is provided below.

Example

As an example, consider a model consisting of ISP_i, ISP_j, and their customers where each provider calculates the volumes of native traffic. Assume that a customer of ISP_i requests data available on ISP_j. Let *N1* be the PPB router of ISP_i, which receives a packet marked by '*1*'. Before forwarding it to ISP_j, *N1* performs the NOT operation on the ML field of the outgoing packet and increases the counter for outgoing native traffic. The PPB node *N2* of ISP_j reads the IP header of the received packet and then forwards it to the destination, e.g., the *N3* node. After receiving the packet, *N3* sends a packet stream with the requested data where the label value of each packet is set to '*0*'. A similar procedure follows on the inverse path with the only difference that ISP_i considers incoming traffic as native, initiated by its own customers. The principle of our traffic management mechanism for peering arrangements is illustrated in Figure 3.1.

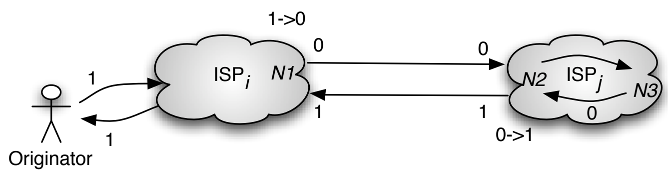


FIGURE 3.1: Traffic Management Mechanism for Peering Arrangement.

Incentive Compatibility

Incentive compatibility of a mechanism is defined as the property when participating providers have no incentive to lie or cheat. It is well known that strategic agents have an incentive not to be truthful and, therefore, end-systems or the defined PPB nodes can perform mendacious packet marking. However, there are several favorable reasons to adopt the proposed approach. First, we considered that PPBs are trust boundaries, therefore, their operations can be recorded and then audited. Second, applying a commonly used pricing scheme, such as a flat-rate, creates no incentive to the end-systems to perform untruthful packet marking since it does not affect their fees and quality of service. Finally, interconnection is a long-term and repeated process, arranged under mutual benefits, and therefore, sustainable cooperation between interconnected ISPs is a reasonable and natural solution. Nevertheless, in Section 4.1.1, we address the incentive compatibility issue that deals with truthful packet marking . The proposed strategy considers peering and transit models.

3.3 Investigating the Inelastic Demand Model

In the following subsection, we analyze the impact of the determination of a transmission initiator on intercarrier compensation between peers. First, we consider a regulated environment with reciprocal access charges (ACs, i.e., equal), and then examine a market model, where providers set non-reciprocal ACs (i.e., the charges are not the same in each direction) without regulation. The studies examine inelastic demand model, where customer demands do not increase or decrease with market price changes.

3.3.1 The Economic Model and its Analyses

In order to investigate the effect of traffic differentiation on the inter-provider payments, we provide analytical studies based on a bargaining process that is explored using *Nash Bargaining Solution* (NBS). It provides a fair and Pareto-efficient outcome. This approach was previously taken in [9], [75]. To capture the traffic imbalances between the providers, we follow the assumption made in [55], and therefore, consider two types of customers, namely websites (which host information and content) and consumers (who use the information and content provided on websites). Actually, traffic is exchanged 1) between consumers, 2) between websites, 3) from websites to consumers, and 4) from consumers to websites. Generally, traffic between websites, between consumers (email exchanges), and from consumers to websites (the requests for websites/file downloads) is much smaller than traffic generated from websites to consumers. Recently, Peer-to-Peer (P2P) traffic has increased rapidly and comprises a significant part of the Internet traffic. According to the proposed approach, a node (a customer) in a P2P network is considered as *a consumer as well as a website simultaneously* since it can act as a client and as a server. Thus, traffic generated from websites to consumers and from consumers to websites along with Web, FTP, and streaming media traffic captures P2P traffic, while traffic between consumers captures email exchange and VoIP traffic that tends to be symmetric. The studies investigate how net interconnection payments between providers depend on the differentiated traffic flows and focus on traffic asymmetry in its simplest way. Hence, they consider traffic exchange i) from consumers to websites and ii) from websites to consumers.

The following assumptions were made to simplify the analytical studies:

Assumption 3.1. *Let* $\alpha_i \in (0,1)$ *be network i's market share for consumers and* $\beta_i \in (0,1)$ *its market share for websites. The market consists of two providers* $i \neq j = 1,2$ *and* $\alpha_i + \alpha_j = 1$*,* $\beta_i + \beta_j = 1$*.*

Assumption 3.2. *For simplicity, a balanced calling pattern*[1] *where each consumer requests any website in any network with the same probability is considered.*

Assumption 3.3. *Each customer chooses only one provider to join because of homogeneity of the services.*

Assumption 3.4. *Each consumer originates one unit of traffic per each request of website and downloads a fixed amount of content. The number of consumers and websites in the market is given by N and M respectively. Hence, the number of consumers and websites subscribed to ISP_i is given by $\alpha_i N$ and $\beta_i M$ respectively.*

3.3.2 Reciprocal Access Charges

We start by examining a scenario in which *ISP_i fails to sign an interconnection agreement with ISP_j*. The utility or benefit of joining ISP_i for each consumer is $u(\beta_i, M) = f(\beta_i)$, and each website's utility is given by $h(\alpha_i, N) = g(\alpha_i)$. The presence of network positive externalities implies that $f'(\cdot) > 0$ and $g'(\cdot) > 0$. In case of disagreement on interconnection between providers, the total traffic volume generated by ISP_i is

$$t_i = \alpha_i \beta_i NM + \alpha_i \beta_i NMx \tag{3.1}$$

where the first component is the volume of traffic exchanged from consumers to websites, the second one denotes the volume of traffic exchanged from websites to consumers, and x is the average amount of traffic caused by requesting a website. It is known that P2P traffic asymmetry is typically caused by less capacity provisioned in the upstream direction. Thus upstream/downstream P2P traffic flows can be asymmetric, which implies that x is different for the customers subscribed to different ISPs. However, this does not affect the results of our studies. The pre-interconnection demand function of network i is described by

$$D_i^{pre} = t_i \quad \textit{if} \quad f(\beta_i) \geq 0 \quad \textit{and} \quad g(\alpha_i) \geq 0$$

Let network i's marginal costs of origination and termination be $c_i^o > 0$ and $c_i^t > 0$ respectively, where $c_i^o = c_i^t$. We do not consider fixed network cost since our goal is to investigate explicit monetary charges between ISPs. The profit of ISP_i from on-net traffic (i.e., destined to the customers of its network) is defined by

$$\pi_i = [\alpha_i N f(\beta_i) + \beta_i M g(\alpha_i)] - t_i(c_i^o + c_i^t) \tag{3.2}$$

where the first two components present the total utility generated by the network and the last component denotes the incremental costs of the network.

[1]Other works make a certain statistical assumption, such as a balanced calling pattern. This is due to the lack of mathematical models on how traffic between networks is distributed.

Suppose that ISP_i obtained an agreement with ISP_j. We assume that the providers' market shares for customers do not change in case of interconnection. In this case each consumer's utility is defined by $u(\beta, M) = f(\beta)$, and each website's utility is given by $h(\alpha, N) = g(\alpha)$. The volumes of the differentiated traffic flows exchanged from ISP_i to ISP_j are calculated as follows

$$\begin{aligned} t_{ij}^{nat} &= \alpha_i \beta_j N M \\ t_{ij}^{str} &= \alpha_j \beta_i N M x \end{aligned} \tag{3.3}$$

where t_{ij}^{nat} and t_{ij}^{str} denote *native* and *stranger* traffic volumes with respect to ISP_i. Similarly, the differentiated traffic volumes from ISP_j to ISP_i are defined by

$$\begin{aligned} t_{ji}^{nat} &= \alpha_j \beta_i N M \\ t_{ji}^{str} &= \alpha_i \beta_j N M x \end{aligned} \tag{3.4}$$

where t_{ji}^{nat} and t_{ji}^{str} denote *native* and *stranger* traffic volumes with respect to ISP_j. Summarizing, the total traffic volumes exchanged between the providers are given by

$$t_{ij} = t_{ij}^{nat} + t_{ij}^{str} \tag{3.5}$$

$$t_{ji} = t_{ji}^{nat} + t_{ji}^{str} \tag{3.6}$$

In case of the agreement, the demand of ISP_i is defined by

$$D_i^{post} = t_i + t_{ij} \quad if \quad f(\beta) \geq 0 \quad and \quad g(\alpha) \geq 0$$

Since it is out of the scope of this thesis to investigate how the access charges are set, in this subsection, we assume that they are defined by an industry regulator and then applied reciprocally. More specifically, the providers charge each other the same access charges a and b for terminating native and stranger traffic respectively, where $a > b$ (since the provider compensates partially the costs of terminating stranger traffic). The access charge b determines how the costs are shared between consumers and websites: the higher access charge for terminating stranger traffic, the higher the per-unit charge to websites. To carry out analysis, the access charge for terminating native traffic is set to the lowest termination marginal cost, and for terminating stranger traffic is defined by $b = \varepsilon a$, $0.5 \leq \varepsilon < 1$. In order to simplify studies, we fix $\varepsilon = 0.5$. It is important to note that the results are robust for the entire interval of ε. The profit of ISP_i obtained interconnection is calculated as follows

$$\Pi_i = \pi_i + \sigma_i \tag{3.7}$$

where σ_i is the incremental profit that ISP_i gets from the interconnection. More specifically, the incremental profit is obtained from off-net traffic exchange, which is destined to the subscribers of another network and is given by

$$\begin{aligned} \sigma_i = \alpha_i N f(\beta) + \beta_i M g(\alpha) + t_{ij}^{nat}(-c_i^o - a) \\ + t_{ij}^{str}(-c_i^o - b) + t_{ji}^{nat}(a - c_i^t) + t_{ji}^{str}(b - c_i^t) \end{aligned} \tag{3.8}$$

The outcome of j's network according to the Nash bargaining game[2] is defined by

$$\Pi_j^{NBS} = 0.5(\Pi_j + \Pi_i + \pi_j - \pi_i) = 0.5(\sigma_i + \sigma_j) + \pi_j$$

where providers equally divide any payoffs relative to the disagreement (or threat) point, which is the payment that providers receive in case of a disrupted connection. If $\sigma_i > \sigma_j$, then ISP_j received the net interconnection payment from ISP_i that is

$$\Pi_j^{NBS} - \Pi_j = 0.5(\sigma_i - \sigma_j) = 0.5\Delta\sigma \tag{3.9}$$

We consider the case when $f''(\cdot) = 0$ and $g''(\cdot) = 0$, so that the network externalities exhibit constant returns to scale. This implies that the networks have the same incremental revenues, while the incremental costs increase as the network size decreases. By substituting (3.8) in (3.9) follows that

$$\begin{aligned} \Pi_j^{NBS} - \Pi_j = 0.5[t_{ji}^{nat}(2a + c_j^o - c_i^t) - t_{ij}^{nat}(2a + c_i^o - c_j^t)] \\ + 0.5[t_{ji}^{str}(2b + c_j^o - c_i^t) - t_{ij}^{str}(2b + c_i^o - c_j^t)] \end{aligned} \tag{3.10}$$

In the DTIA model, the net interconnection charge is interpreted as two independent components i) one for a native traffic business, which is denoted by σ_{ij}^{nat}, and ii) another for a stranger traffic business that is denoted by σ_{ij}^{str}. Summarizing

$$\sigma_{ij}^{nat} = 0.5[t_{ji}^{nat}(2a + c_j^o - c_i^t) - t_{ij}^{nat}(2a - (c_j^t - c_i^o))] \tag{3.11}$$

$$\sigma_{ij}^{str} = 0.5[t_{ji}^{str}(2b + c_j^o - c_i^t) - t_{ij}^{str}(2b - (c_j^t - c_i^o))] \tag{3.12}$$

The following analyses explore how the interconnection payments depend on the differentiated traffic flows, which are determined by providers' market shares for consumers and websites. For this purpose, we consider all available market states in terms of providers' sizes (i.e., market shares). It is obvious that the total number of all alternative states of the market, where the providers have θ market shares, can be expressed as 2^θ. Excluding identical cases, we obtained the five states which are investigated below.

[2] A bargaining game for two players is defined as a situation where players must reach an agreement on an outcome in a set of possible joint utility allocations (possible agreements).

Proposition 3.1. *The net payment from ISP$_i$ to ISP$_j$ is increasing in t_{ji}^{nat} and t_{ji}^{str}.*

Proof. Partially differentiating $\Delta\sigma$ with respect to the corresponding parameters follows

$$\frac{\partial \Delta\sigma}{\partial t_{ij}^{nat}} \begin{cases} > 0 & \text{if } c_j^t > 2a + c_i^o \\ = 0 & \text{if } c_j^t = 2a + c_i^o \\ < 0 & \text{if } c_j^t < 2a + c_i^o \end{cases} \qquad \frac{\partial \Delta\sigma}{\partial t_{ij}^{str}} \begin{cases} > 0 & \text{if } c_j^t > 2b + c_i^o \\ = 0 & \text{if } c_j^t = 2b + c_i^o \\ < 0 & \text{if } c_j^t < 2b + c_i^o \end{cases}$$

$$\frac{\partial \Delta\sigma}{\partial t_{ji}^{nat}} = (2a + c_j^o - c_i^t) > 0 \qquad \frac{\partial \Delta\sigma}{\partial t_{ji}^{str}} = (2b + c_j^o - c_i^t) > 0$$

This implies that the more incoming traffic to ISP$_i$, the more benefit of the provider. □

Proposition 3.2. *If $\alpha_i = \alpha_j$ and $\beta_i = \beta_j$, then net interconnection payments between providers are zero.*

Proof. Given the symmetry of the model in terms of size, then $c_i^t = c_j^t = a$. From the conditions (3.3) and (3.4) follows that $t_{ij}^{nat} = t_{ji}^{nat}$ and $t_{ij}^{str} = t_{ji}^{str}$. As a result, it is straightforward to show that the net interconnection transfers are given by $(\Pi_i^{NBS} - \Pi_i) = (\Pi_j^{NBS} - \Pi_j) = 0$. □

Proposition 3.3. *If $\alpha_i = \alpha_j$ and $\beta_i > \beta_j$, then ISP$_i$ subsidizes ISP$_j$ for native traffic.*

Proof. In this case $c_i^t < c_j^t$ and $a = c_i^t$, because $\alpha_i = \alpha_j$ and $\beta_i > \beta_j$.
Native: From the conditions (3.3) and (3.4) follows that $t_{ij}^{nat} < t_{ji}^{nat}$. Given that $c_i^t < c_j^t$ and the component of the native traffic business (3.11), then $(2a + c_j^o - c_i^t) > (2a - (c_j^t - c_i^o))$. Hence, we obtain that $\sigma_{ij}^{nat} > 0$. In this case, ISP$_i$ gets higher profit from native traffic exchange than ISP$_j$ and therefore subsidizes the rival network.
Stranger: From the equations (3.3) and (3.4) follows that $t_{ij}^{str} > t_{ji}^{str}$. The component of the stranger traffic business (3.12), where $(2b + c_j^o - c_i^t) > (2b - (c_j^t - c_i^o))$ is not straightforward and is defined by

$$\sigma_{ij}^{str} \begin{cases} > 0 & \text{if } t_{ji}^{str}/t_{ij}^{str} > (2c_i^t - c_j^t)/c_j^o \\ = 0 & \text{if } t_{ji}^{str}/t_{ij}^{str} = (2c_i^t - c_j^t)/c_j^o \\ < 0 & \text{if } t_{ji}^{str}/t_{ij}^{str} < (2c_i^t - c_j^t)/c_j^o \end{cases} \tag{3.13}$$

□

Proposition 3.4. *If $\alpha_i > \alpha_j$ and $\beta_i = \beta_j$, then ISP$_i$ subsidizes ISP$_j$ for stranger traffic.*

Proof. Given that ISP$_i$ is larger than ISP$_j$, then $c_i^t < c_j^t$ and $a = c_i^t$.
Native: From the conditions (3.3) and (3.4) follows that $t_{ij}^{nat} > t_{ji}^{nat}$. Considering the native traffic business, the condition (3.11) is not straightforward and is given by

$$\sigma_{ij}^{nat} \begin{cases} > 0 & \text{if } t_{ij}^{nat}/t_{ji}^{nat} < (a + c_j^o)/(2a + c_i^o - c_j^t) \\ = 0 & \text{if } t_{ij}^{nat}/t_{ji}^{nat} = (a + c_j^o)/(2a + c_i^o - c_j^t) \\ < 0 & \text{if } t_{ij}^{nat}/t_{ji}^{nat} > (a + c_j^o)/(2a + c_i^o - c_j^t) \end{cases} \qquad (2a + c_i^o - c_j^t) \neq 0 \tag{3.14}$$

Stranger: Examining the equations (3.3) and (3.4), we obtain that $t_{ij}^{str} < t_{ji}^{str}$. From (3.12) follows that $\sigma_{ij}^{str} > 0$, and thus ISP$_j$ receives net payments for stranger traffic from ISP$_i$. □

When $\alpha_i > \alpha_j$ and $\beta_i > \beta_j$, the following cases for the traffic volumes are obtained from the expressions (3.5) and (3.6): 1) $t_{ij} > t_{ji}$, 2) $t_{ij} < t_{ji}$, and 3) $t_{ij} = t_{ji}$. The cases 1) and 2) are analogous to those described above. The case when $t_{ij} = t_{ji}$ is analyzed below.

Proposition 3.5. *If $\alpha_i > \alpha_j$, $\beta_i > \beta_j$, and $t_{ij} = t_{ji}$, then $\alpha_i = \beta_i$.*

Proof. The result is obtained from (3.5) and (3.6) that is

$$\alpha_i \beta_j NM + \alpha_j \beta_i MNx = \alpha_j \beta_i NM + \alpha_i \beta_j MNx$$

This gives $\alpha_i(1 - \beta_i) - \beta_i(1 - \alpha_i) = \alpha_i - \beta_i = 0 => \alpha_i = \beta_i$.

□

Corollary 3.1. *If $\alpha_i > \alpha_j$, $\beta_i > \beta_j$, and $t_{ij} = t_{ji}$, then $t_{ij}^{nat} = t_{ji}^{nat}$ and $t_{ij}^{str} = t_{ji}^{str}$.*

Proposition 3.6. *If $\alpha_i > \alpha_j$, $\beta_i > \beta_j$, and $t_{ij} = t_{ji}$, then ISP$_i$ subsidizes ISP$_j$ for native and stranger traffic.*

Proof. In this case $c_i^t < c_j^t$ and $a = c_i^t$, because $\alpha_i > \alpha_j$ and $\beta_i > \beta_j$.
Native: Considering the native traffic component (3.11) when $t_{ij}^{nat} = t_{ji}^{nat}$, it can be obtained that $\sigma_{ij}^{nat} > 0$. Here, ISP$_i$ receives higher incremental profit than the rival network and consequently subsidizes ISP$_j$.
Stranger: Given $t_{ij}^{str} = t_{ji}^{str}$, from the condition (3.12) follows that $\sigma_{ij}^{str} > 0$. Under symmetric stranger traffic flows, ISP$_j$ receives net interconnection charges. □

Allowing that $\alpha_i > \alpha_j$, $\beta_i < \beta_j$, and recalling that costs are higher for the smaller network than for the larger network, the following cases for the termination costs are possible: 1) $c_i^t > c_j^t$, 2) $c_i^t < c_j^t$, and 3) $c_i^t = c_j^t$. The cases 1) and 2) are similar to those described above. The last case when the networks are equal in terms of size is examined below.

Proposition 3.7. *If $\alpha_i > \alpha_j$, $\beta_i < \beta_j$, and $c_i^t = c_j^t = a$, then ISP$_i$ (ISP$_j$) subsidizes ISP$_j$ (ISP$_i$) for stranger (native) traffic.*

Proof. Given that the networks are equal in terms of size, then $\alpha_i N + \beta_i M = \alpha_j N + \beta_j M$. This gives $\alpha_i N = \beta_j M$ and $\alpha_j N = \beta_i M$.
Native: From the conditions (3.3) and (3.4) follows that $t_{ij}^{nat} > t_{ji}^{nat}$. Considering the native traffic business component (3.11), we obtain that $\sigma_{ij}^{nat} < 0$. In this case, ISP$_i$ receives net payments from ISP$_j$.
Stranger: Considering the equations (3.3) and (3.4), it can be obtained that $t_{ij}^{str} < t_{ji}^{str}$. From the equation (3.12) follows that $\sigma_{ij}^{str} > 0$, and consequently, ISP$_j$ receives net payments from ISP$_i$. □

3.3.3 Non-reciprocal Access Charges

In this subsection, we explore how interconnection payments depend on the differentiated traffic flows when the providers set non-reciprocal access charges. Let a_i and b_i be network i's access charges for terminating native and stranger traffic respectively, where $a_i > b_i$ (in DTIA, the charges for terminating stranger traffic are less than the charges for terminating native traffic). To carry out our analysis, we assume that the network's access charge for terminating native traffic is set to the termination marginal cost, i.e., $a_i = c_i^t$, and access charge for terminating stranger traffic is defined by $b_i = \varepsilon a_i$, where $0.5 \leq \varepsilon < 1$. The variable ε is the same for both networks and for simplicity is set to $\varepsilon = 0.5$. By substituting these access charges in equation (3.8), the incremental profit of ISP$_i$ obtained from the interconnection can be re-written as follows

$$\begin{aligned}\sigma_i = \alpha_i N f(\beta) + \beta_i M g(\alpha) + t_{ij}^{nat}(-c_i^o - a_j) \\ + t_{ij}^{str}(-c_i^o - b_j) + t_{ji}^{nat}(a_i - c_i^t) + t_{ji}^{str}(b_i - c_i^t)\end{aligned} \tag{3.15}$$

The net payment from ISP$_i$ to ISP$_j$ (i.e., when $\sigma_i > \sigma_j$) is obtained by substituting (3.15) in (3.9) and is given by

$$\begin{aligned}\Pi_j^{NBS} - \Pi_j = 0.5\left[t_{ji}^{nat}(2a_i + c_j^o - c_i^t) - t_{ij}^{nat}(2a_j + c_i^o - c_j^t)\right] \\ + 0.5\left[t_{ji}^{str}(2b_i + c_j^o - c_i^t) - t_{ij}^{str}(2b_j + c_i^o - c_j^t)\right]\end{aligned} \tag{3.16}$$

According to the proposed approach, the net interconnection charge is considered as two independent components i) one for a native traffic business, which is denoted by σ_{ij}^{nat}, and ii) another for a stranger traffic business which is denoted by σ_{ij}^{str}. Summarizing

$$\sigma_{ij}^{nat} = 0.5\left[t_{ji}^{nat}(2a_i + c_j^o - c_i^t) - t_{ij}^{nat}(2a_j - (c_j^t - c_i^o))\right] \tag{3.17}$$

$$\sigma_{ij}^{str} = 0.5\left[t_{ji}^{str}(2b_i + c_j^o - c_i^t) - t_{ij}^{str}(2b_j - (c_j^t - c_i^o))\right] \tag{3.18}$$

Analogous to the previous studies which considered reciprocal access charges, the following analyses examine all available market states in terms of market shares.

Proposition 3.8. *The net payment from ISP*$_i$ *(ISP*$_j$*) to ISP*$_j$ *(ISP*$_i$*) is a) increasing in* t_{ji}^{nat} *and* t_{ji}^{str} *(*t_{ij}^{nat} *and* t_{ij}^{str}*), and b) decreasing in* t_{ij}^{nat} *and* t_{ij}^{str} *(*t_{ji}^{nat} *and* t_{ji}^{str}*).*

Proof. Partially differentiating $\Delta\sigma$ with respect to the corresponding parameters gives

$$\frac{\partial \Delta\sigma}{\partial t_{ij}^{nat}} = -(2a_j + c_i^o - c_j^t) < 0 \qquad \frac{\partial \Delta\sigma}{\partial t_{ji}^{nat}} = (2a_i + c_j^o - c_i^t) > 0$$

$$\frac{\partial \Delta\sigma}{\partial t_{ij}^{str}} = -(2b_j + c_i^o - c_j^t) < 0 \qquad \frac{\partial \Delta\sigma}{\partial t_{ji}^{str}} = (2b_i + c_j^o - c_i^t) > 0$$

It can be noticed that the more incoming traffic, the more benefit of the provider. □

Proposition 3.9. *If* $\alpha_i = \alpha_j$ *and* $\beta_i = \beta_j$*, then net interconnection payments between providers are zero.*

Proof. Given that the networks are symmetric in terms of size, then $c_i^t = c_j^t$. Using the condition (3.16), it is straightforward to show that the net transfers are given by $(\Pi_i^{NBS} - \Pi_i) = (\Pi_j^{NBS} - \Pi_j) = 0$. □

Proposition 3.10. *If* $\alpha_i = \alpha_j$ *and* $\beta_i > \beta_j$*, then ISP*$_i$ *subsidizes ISP*$_j$ *for native traffic.*

Proof. In this case $c_i^t < c_j^t$, because ISP$_i$ is larger than ISP$_j$.
Native: From the equations (3.3) and (3.4), it can be obtained that $t_{ij}^{nat} < t_{ji}^{nat}$. Given that $c_i^t < c_j^t$ and the component of the native traffic business (3.17), then $(2a_i + c_j^o - c_i^t) = (2a_j - (c_j^t - c_i^o))$. Hence, we obtain that $\sigma_{ij}^{nat} > 0$. This implies that ISP$_i$ receives higher incremental profit from native traffic exchange and consequently subsidizes ISP$_j$.
Stranger: Following (3.3) and (3.4), it can be obtained that $t_{ij}^{str} > t_{ji}^{str}$. The stranger traffic business component (3.18), where $(2b_i + c_j^o - c_i^t) > (2b_j - (c_j^t - c_i^o))$, is not straightforward. Summarizing

$$\sigma_{ij}^{str} \begin{cases} > 0 & \text{if } t_{ij}^{str}/t_{ji}^{str} < c_j^o/c_i^o \\ = 0 & \text{if } t_{ij}^{str}/t_{ji}^{str} = c_j^o/c_i^o \\ < 0 & \text{if } t_{ij}^{str}/t_{ji}^{str} > c_j^o/c_i^o \end{cases} \tag{3.19}$$

□

Proposition 3.11. *If $\alpha_i > \alpha_j$ and $\beta_i = \beta_j$, then ISP$_i$ (ISP$_j$) subsidizes ISP$_j$ (ISP$_i$) for stranger (native) traffic.*

Proof. Given that $\alpha_i > \alpha_j$ and $\beta_i = \beta_j$, then $c_i^t < c_j^t$.
Native: From the conditions (3.3) and (3.4) follows that $t_{ij}^{nat} > t_{ji}^{nat}$. Following (3.17), the net payment for native traffic is given by $\sigma_{ij}^{nat} < 0$. Hence, ISP$_j$ gets higher incremental profit than ISP$_i$ from native traffic exchange and subsidizes the peered network.
Stranger: Using (3.3) and (3.4), it can be obtained that $t_{ij}^{str} < t_{ji}^{str}$. Considering the component of the stranger traffic business (3.18) it follows that $\sigma_{ij}^{str} > 0$. In this case, ISP$_j$ receives net interconnection charges for stranger traffic from ISP$_i$. □

Recall that, when $\alpha_i > \alpha_j$ and $\beta_i > \beta_j$, the following cases for the traffic volumes are obtained from conditions (3.5) and (3.6): 1) $t_{ij} > t_{ji}$, 2) $t_{ij} < t_{ji}$, and 3) $t_{ij} = t_{ji}$. The last case is considered further since the cases 1) and 2) are analogous to those described above.

Proposition 3.12. *If $\alpha_i > \alpha_j$, $\beta_i > \beta_j$, and $t_{ij} = t_{ji}$, then ISP$_i$ subsidizes ISP$_j$ for stranger traffic.*

Proof. From the definition where ISP$_i$ is larger than ISP$_j$ follows that $c_i^t < c_j^t$.
Native: Using Corollary 3.1, which gives that $t_{ij}^{nat} = t_{ji}^{nat}$, the net payment for native traffic is given by $\sigma_{ij}^{nat} = 0$. Consequently, the providers' incremental profits obtained from exchange of symmetric traffic volumes are equal.
Stranger: From Corollary 3.1 and the component of the stranger traffic business (3.18) follows that $\sigma_{ij}^{str} > 0$. The result indicates that, under symmetric stranger traffic volumes, ISP$_j$ receives net interconnection charges. □

When $\alpha_i > \alpha_j$ and $\beta_i < \beta_j$, the following cases for the termination costs are obtained: 1) $c_i^t > c_j^t$, 2) $c_i^t < c_j^t$, and 3) $c_i^t = c_j^t$. Since the cases 1) and 2) are similar to those described above, we examine the last case 3).

Proposition 3.13. *If $\alpha_i > \alpha_j$, $\beta_i < \beta_j$, and $c_i^t = c_j^t$, then ISP$_i$ (ISP$_j$) subsidizes ISP$_j$ (ISP$_i$) for stranger (native) traffic.*

Proof. Symmetry of networks in terms of size implies that $\alpha_i N = \beta_j M$ and $\beta_i M = \alpha_j N$.
Native: From the conditions (3.3) and (3.4) follows that $t_{ij}^{nat} > t_{ji}^{nat}$. Considering the native traffic business component (3.17), it can be obtained that $\sigma_{ij}^{nat} < 0$. Thus, ISP$_i$ is compensated by ISP$_j$ for the costs incurred in carrying native traffic.

Case	α	β	c^t	t^{nat}	t^{str}
I	$\alpha_i = \alpha_j$	$\beta_i = \beta_j$	$c_i^t = c_j^t$	$t_{ij}^{nat} = t_{ji}^{nat}$	$t_{ij}^{str} = t_{ji}^{str}$
II	$\alpha_i = \alpha_j$	$\beta_i > \beta_j$	$c_i^t < c_j^t$	$t_{ij}^{nat} < t_{ji}^{nat}$	$t_{ij}^{str} > t_{ji}^{str}$
III	$\alpha_i > \alpha_j$	$\beta_i = \beta_j$	$c_i^t < c_j^t$	$t_{ij}^{nat} > t_{ji}^{nat}$	$t_{ij}^{str} < t_{ji}^{str}$
IV	$\alpha_i > \alpha_j$	$\beta_i > \beta_j$	$c_i^t < c_j^t$	*if* $t_{ij}^{nat} = t_{ji}^{nat}$	*if* $t_{ij}^{str} = t_{ji}^{str}$
V	$\alpha_i > \alpha_j$	$\beta_i < \beta_j$	*if* $c_i^t = c_j^t$	$t_{ij}^{nat} > t_{ji}^{nat}$	$t_{ij}^{str} < t_{ji}^{str}$

TABLE 3.1: Results of the DTIA Model with Inelastic Demand.

Stranger: Considering the conditions (3.3) and (3.4), we obtain that $t_{ij}^{str} < t_{ji}^{str}$. The component of the stranger traffic business (3.18) is given by $\sigma_{ij}^{str} > 0$. In this case, ISP$_j$ receives net payments for stranger traffic exchange from ISP$_i$. □

3.3.4 Discussion

We now summarize the results obtained from the analytical studies which considered symmetric and asymmetric access charges (see Tables 3.1-3.4). Tables 3.1 and 3.2 demonstrate the correlation between the differentiated traffic flows and providers' market shares. Table 3.3 reports how the net payments between peering ISPs depend on the distinguished traffic types. The comparison of the interconnection charges between agreements based on the net traffic flow (TF) and differentiated traffic flows compensations are presented in Table 3.4. In order to calculate the specific outcomes, we impose the following values of termination costs in the model with reciprocal access charges i) $c_i^t = c_j^t = 1$ in cases I and V, ii) $c_i^t = 1$, $c_j^t = 1.5$ in all other cases. The termination costs in the model with non-reciprocal access rates are set as follows i) $c_i^t = c_j^t = 1$ in cases I and V, ii) $c_i^t = 1$, $c_j^t = 2$ in all other cases. Other parameters are $x = 35$, $N = 100$, and $M = 60$. The market shares for case V were obtained so that the size of each network is equal to $0.5(N + M)$. The parameters are chosen to be reasonable to examine all available market states in terms of providers' market shares. However, the specification is clearly arbitrary. It is important to note that our conclusions do not heavily depend on the chosen parameter values (see Tables 3.1 and 3.3). The results obtained for a number of other parameter sets have not produced significant changes.

The net payments in the classical model, i.e., based on the net traffic flow compensation, with reciprocal and non-reciprocal access charges are calculated as follows

$$\Pi_j^{NBS} - \Pi_j = 0.5\left[t_{ji}(2a + c_j^o - c_i^t) - t_{ij}(2a + c_i^o - c_j^t)\right]$$
$$\Pi_j^{NBS} - \Pi_j = 0.5\left[t_{ji}(2a_i + c_j^o - c_i^t) - t_{ij}(2a_j + c_i^o - c_j^t)\right]$$

Case	α_i	β_i	t_{ij}^{nat}	t_{ij}^{str}	t_{ji}^{nat}	t_{ji}^{str}	t_{ij}	t_{ji}
I	0.5	0.5	1500	52500	1500	52500	54000	54000
II	0.5	0.9	300	94500	2700	10500	94800	13200
	0.5	0.8	600	84000	2400	21000	84600	23400
	0.5	0.773	682	81136	2318	23864	81818	26182
	0.5	0.7	900	73500	2100	31500	74400	33600
	0.5	0.677	970	71061	2030	33939	72030	35970
	0.5	0.6	1200	63000	1800	42000	64200	43800
III	0.9	0.5	2700	10500	300	94500	13200	94800
	0.8	0.5	2400	21000	600	84000	23400	84600
	0.7	0.5	2100	31500	900	73500	33600	74400
	0.6	0.5	1800	42000	1200	63000	43800	64200
IV	0.9	0.9	540	18900	540	18900	19440	19440
$\alpha_i = \beta_i$	0.8	0.8	960	33600	960	33600	34560	34560
	0.7	0.7	1260	44100	1260	44100	45360	45360
	0.6	0.6	1440	50400	1440	50400	51840	51840
V	0.7	0.167	3500	10500	300	122501	14000	122801
$\alpha_i N = \beta_j M$	0.65	0.25	2925	18375	525	102375	21300	102900
	0.6	0.333	2400	28000	800	84000	30400	84800
	0.55	0.417	1924	39407	1126	67337	41330	68462

TABLE 3.2: Traffic Differentiation of the DTIA Model.

Case	Reciprocal ACs		Non-reciprocal ACs	
	σ^{nat}	σ^{str}	σ^{nat}	σ^{str}
I	$\sigma_{ij}^{nat} = \sigma_{ji}^{nat}$	$\sigma_{ij}^{str} = \sigma_{ji}^{str}$	$\sigma_{ij}^{nat} = \sigma_{ji}^{nat}$	$\sigma_{ij}^{str} = \sigma_{ji}^{str}$
II	$\sigma_{ij}^{nat} > \sigma_{ji}^{nat}$	eq. (3.13)	$\sigma_{ij}^{nat} > \sigma_{ji}^{nat}$	eq. (3.19)
III	eq. (3.14)	$\sigma_{ij}^{str} > \sigma_{ji}^{str}$	$\sigma_{ij}^{nat} < \sigma_{ji}^{nat}$	$\sigma_{ij}^{str} > \sigma_{ji}^{str}$
IV	$\sigma_{ij}^{nat} > \sigma_{ji}^{nat}$	$\sigma_{ij}^{str} > \sigma_{ji}^{str}$	$\sigma_{ij}^{nat} = \sigma_{ji}^{nat}$	$\sigma_{ij}^{str} > \sigma_{ji}^{str}$
V	$\sigma_{ij}^{nat} < \sigma_{ji}^{nat}$	$\sigma_{ij}^{str} > \sigma_{ji}^{str}$	$\sigma_{ij}^{nat} < \sigma_{ji}^{nat}$	$\sigma_{ij}^{str} > \sigma_{ji}^{str}$

TABLE 3.3: Interconnection Payments of the DTIA Model with Inelastic Demand.

Several conclusions can be made from the obtained results (see Tables 3.1-3.4). They demonstrated that, under certain market shares, the net payment of ISP$_i$ for a particular type of traffic is the same as that of ISP$_j$ for another type of traffic (see Tables 3.4, case II). More specifically, $\sigma_{ij}^{nat} + \sigma_{ij}^{str} = 0$, and asymmetric providers decide to interconnect without monetary transfers. On the other side, symmetric providers in terms of size (i.e., cost structures are symmetric) can benefit differently due to the different market shares for consumers and websites (see Tables 3.4, case V).

The results also showed that generally, in spite of termination costs, the more incoming traffic of a particular type, the more provider benefits from that type of traffic. The comparison of the symmetric cases in terms of the originated traffic volumes (presented

Case	Reciprocal ACs				Non-reciprocal ACs			
	σ_{ij}^{nat}	σ_{ij}^{str}	$\Delta\sigma/2$		σ_{ij}^{nat}	σ_{ij}^{str}	$\Delta\sigma/2$	
			DTIA	**TF**			**DTIA**	**TF**
I	0	0	0	0	0	0	0	0
II	3150	-15750	-12600	-54600	3600	-36750	-33150	-122400
	2550	-5250	-2700	-34200	2700	-21000	-18300	-91800
	2386	-2386	0	-28636	2455	-16705	-14250	-83454
	1950	5250	7200	-13800	1800	-5250	-3450	-61200
	811	7689	9500	-9060	1591	-1591	0	-54091
	1350	15750	17100	6600	900	1050	11400	-30600
III	-1650	68250	66600	108600	-3600	89250	85650	122400
	-1050	57750	56700	88200	-2700	73500	70800	91800
	-450	47250	46800	67800	-1800	57750	55950	61200
	150	36750	36900	47400	-900	42000	41100	30600
IV	270	9450	9720	9720	0	9450	9450	0
	480	16800	17280	17280	0	16800	16800	0
	630	22050	22680	22680	0	22050	22050	0
	720	25200	25920	25920	0	25200	25200	0
V	-3200	56001	52801	108801	-3200	56001	52801	108801
	-2400	42000	39600	81600	-2400	42000	39600	81600
	-1600	28000	26400	54400	-1600	28000	26400	54400
	-798	13965	13167	27132	-798	13965	13167	27132

TABLE 3.4: Comparative Results of the Agreements Based on the Net Traffic Flow and DT Flows Compensations.

in cases II and III of Tables 3.4) showed that, in DTIA, the net payments that subsidizes the smaller ISP_j in case II is much less than the net payments subsidized by the larger ISP_i in case III. Moreover, at certain market shares, the larger provider compensates the smaller provider. And finally, the outcomes of the presented model deviate less from the Nash solution (which is the same in both models) than the outcomes of the classical model. As a consequence, the proposed strategy significantly reduces the interconnection payments. Overall, it can be concluded that DTIA achieves a more fair solution for the interconnected providers since it diminishes the inequity in cost allocation.

3.4 Investigating the Elastic Demand Model

This section expands our studies considering the elastic demand model[3] and explores the role of traffic differentiation in the wholesale and retail markets. In particular, it examines how beneficial the determination of a transmission initiator is to both customers and providers. As in the previous section, analytical studies are based on the bargaining process that is explored using NBS. In order to focus on explicit monetary transfers and on traffic asymmetry in its simplest way, we examine traffic exchange i) from consumers

[3]The elastic demand model, where customer demands increase or decrease with market price changes.

to websites and ii) from websites to consumers. The studies are provided under the Assumptions 3.1-3.3 and the following

Assumption 3.5. *For simplicity, the number of consumers and the number of websites are normalized to one.*

3.4.1 The Economic Model and its Analyses

Demand Structure

We examine a scenario where ISP_i has signed an interconnection agreement with ISP_j. Each customer derives utility from sending and receiving traffic. Let q_i be an individual demand, i.e., the traffic volume originated by a particular customer. The marginal utility of consuming connection services is defined by

$$u(q_i) = (\gamma - 0.5q_i)q_i$$

Given I income, a customer tries to solve the following problem subject to the budget constraint

$$\max_{q_i} [u(q_i) - p_i q_i] \quad \text{s.t. } p_i q_i + m \leq I \tag{3.20}$$

where p_i is a price for the consumption of connection services and m denotes the consumption of all other goods. By substituting the utility function in (3.20) and solving the consumer surplus maximization problem, the level of traffic that optimizes the customer's utility is defined by

$$\frac{\partial}{\partial q_i} [(\gamma - 0.5q_i)q_i - p_i q_i] = \gamma - q_i - p_i = 0$$

which gives

$$q_i(p_i) = \gamma - p_i \tag{3.21}$$

The indirect utility[4] of a customer is calculated by substituting (3.21) in the maximization problem (3.20) and is given by the following equation

$$\upsilon(p_i) = \left(\gamma - \frac{\gamma - p_i}{2}\right)(\gamma - p_i) - p_i(\gamma - p_i) = \frac{(\gamma - p_i)^2}{2} \tag{3.22}$$

Analytical studies are provided using a *receiver pays principle* [27]. This approach is taken previously in [36]. Let p_i^s and p_i^r ($\tilde{p}_i^s$ and $\tilde{p}_i^r$) be the network i's prices that a subscribed consumer (a hosted website) pays for sending and receiving a unit of traffic

[4] The indirect utility function $\upsilon(p, y)$ is the consumer's maximum utility when the price is p and the income is y.

respectively. Hence, the overall net utility derived by a consumer and a website of ISP_i is defined as a function of the costs associated with originating and receiving traffic. It is calculated as follows

$$U_i = [u(q_i^s) - p_i^s q_i^s] + \left[u(\tilde{q}_j^s) - p_i^r \tilde{q}_j^s\right] \tag{3.23}$$

$$\tilde{U}_i = [u(\tilde{q}_i^s) - \tilde{p}_i^s \tilde{q}_i^s] + \left[u(q_j^s) - \tilde{p}_i^r q_j^s\right] \tag{3.24}$$

where q_i^s ($\tilde{q}_i^s$) is the amount of traffic originated by a consumer (a website) of ISP_i. Since each consumer of the network i initiates q_i requests, the total amount of traffic originated by IPS_i is $\alpha_i q_i$, where β_j proportion goes to ISP_j. Analogously, network i's website originates $\tilde{q}_i$ traffic, and α_j proportion of it is terminated in ISP_j. As a result, the amount of native and stranger traffic from ISP_i to ISP_j is defined by

$$\begin{aligned} t_{ij}^{nat} &= \alpha_i \beta_j q_i^s \\ t_{ij}^{str} &= \alpha_j \beta_i \tilde{q}_i^s \end{aligned} \tag{3.25}$$

Similarly, q_j ($\tilde{q}_j$) traffic is generated by each consumer (website) of ISP_j, and the proportion β_i (α_i) is destined for the peered network. Hence, the amount of native and stranger traffic originating in ISP_j and terminating in ISP_i is given by

$$\begin{aligned} t_{ji}^{nat} &= \alpha_j \beta_i q_j^s \\ t_{ji}^{str} &= \alpha_i \beta_j \tilde{q}_j^s \end{aligned} \tag{3.26}$$

Summarizing, the total traffic volumes originated by the providers present the sum of native and stranger traffic volumes and are calculated as follows

$$\begin{aligned} t_{ij} &= t_{ij}^{nat} + t_{ij}^{str} \\ t_{ji} &= t_{ji}^{nat} + t_{ji}^{str} \end{aligned}$$

Because a *receiver pays principle* is considered, q_i^s and $\tilde{q}_i^s$ depend not only on the price charged by the customer's provider, but also on the price that the rival network charges the receiver to terminate traffic. Consequently, at equilibrium between the exchanged traffic, the amount of traffic originated by a consumer and a website of ISP_i and ready to be accepted in the peered network corresponds to the minimum level of communications and is given by

$$\begin{aligned} q_i^s &= min\left\{\gamma - p_i^s, \gamma - \tilde{p}_j^r\right\} \\ \tilde{q}_i^s &= min\left\{\gamma - \tilde{p}_i^s, \gamma - p_j^r\right\} \end{aligned} \tag{3.27}$$

From (3.27) follows that

$$\begin{aligned}
&\text{if } \gamma - p_i^s - (\gamma - \tilde{p}_j^r) \geq 0, p_i^s \leq \tilde{p}_j^r \quad \text{then } q_i^s = \gamma - \tilde{p}_j^r \\
&\text{else } q_i^s = \gamma - p_i^s \\
&\text{if } \gamma - \tilde{p}_i^s - (\gamma - p_j^r) \geq 0, \tilde{p}_i^s \leq p_j^r \quad \text{then } \tilde{q}_i^s = \gamma - p_j^r \\
&\text{else } \tilde{q}_i^s = \gamma - \tilde{p}_i^s
\end{aligned}$$

The results may be summarized in the following way

$$q_i^s = \begin{cases} \gamma - p_i^s & \text{if } p_i^s \geq \tilde{p}_j^r \\ \gamma - \tilde{p}_j^r & \text{if } p_i^s \leq \tilde{p}_j^r \end{cases} \tag{3.28}$$

$$\tilde{q}_i^s = \begin{cases} \gamma - \tilde{p}_i^s & \text{if } \tilde{p}_i^s \geq p_j^r \\ \gamma - p_j^r & \text{if } \tilde{p}_i^s \leq p_j^r \end{cases} \tag{3.29}$$

Since providers get compensated for utilization of their infrastructures, we assume that prices for receiving traffic are lower then prices for sending traffic, i.e., $p_i^s > \tilde{p}_j^r$ and $\tilde{p}_i^s > p_j^r$. Figure 3.2 demonstrates the inverse demand functions, which are truncated compared to the standard one.

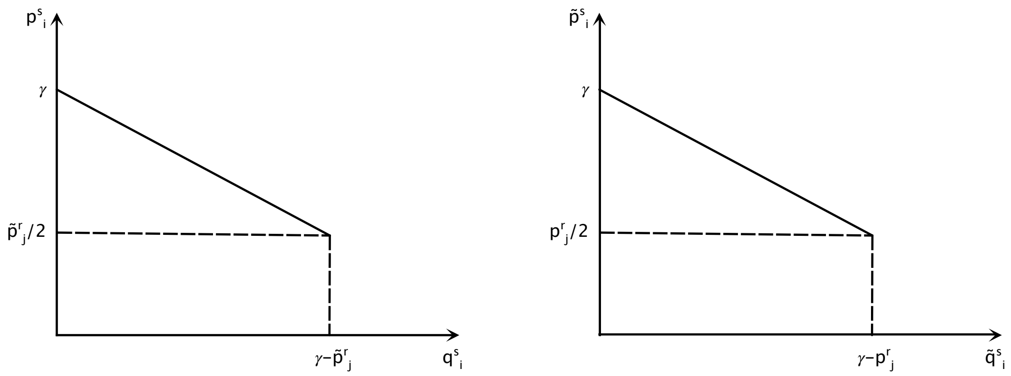


Figure 3.2: Demand Functions.

3.4.2 Reciprocal Access Charges

We start by examining a market with reciprocal access charges which are set by an industry regulator and then applied reciprocally. The cost structure is the same as in the previous section, viz., network i's marginal costs of origination and termination are $c_i^o > 0$ and $c_i^t > 0$ respectively, where $c_i^o = c_i^t$. The providers charge each other the same access charges a and b for terminating native and stranger traffic respectively, where

$a > b$. We follow the assumption made earlier and set the access charge for terminating native traffic to the lowest termination marginal cost; the access charge for terminating stranger traffic is defined by $b = \varepsilon a$, where $0.5 \leq \varepsilon < 1$ (but for simplicity is fixed $\varepsilon = 0.5$). The marginal (i.e., incremental) costs exhibit increasing returns to scale, meaning that the incremental costs of network increase as the network size decreases. For simplicity, fixed network costs are normalized to zero. Also, in this section, the model ignores on-net traffic since it is focused on explicit monetary transfers between providers. The incremental profit that ISP_i obtains from the interconnection is calculated as follows

$$\begin{aligned} \Pi_i = \alpha_i \beta_j \left(p_i^s - c_i^o - a\right) q_i^s + \alpha_j \beta_i \left(\tilde{p}_i^s - c_i^o - b\right) \tilde{q}_i^s \\ + \alpha_j \beta_i \left(\tilde{p}_i^r + a - c_i^t\right) q_j^s + \alpha_i \beta_j \left(p_i^r + b - c_i^t\right) \tilde{q}_j^s \end{aligned} \tag{3.30}$$

where Π_i presents the sum of different components: the profit obtained from traffic originated by the customers of the network, i.e., consumers and websites, and the profit obtained from incoming traffic which is originated by the other network.

Retail Prices

Consider the case when the providers choose the level of the exchanged traffic in order to maximize their profits. This demand has to be lower than, or equal to, a certain value and is given by

$$\begin{aligned} &\max_{q_i^s} \Pi_i \text{s.t } q_i^s \leq \gamma - \tilde{p}_j^r \\ &\max_{\tilde{q}_i^s} \Pi_i \text{s.t } \tilde{q}_i^s \leq \gamma - p_j^r \end{aligned} \tag{3.31}$$

Using the equations (3.28) and (3.29) follows

$$\begin{aligned} &\text{if } q_i^s = \gamma - p_i^s \text{ then } p_i^s = \gamma - q_i^s \\ &\text{if } \tilde{q}_i^s = \gamma - \tilde{p}_i^s \text{ then } \tilde{p}_i^s = \gamma - \tilde{q}_i^s \end{aligned} \tag{3.32}$$

The first order conditions for the profit maximization after the replacement (3.32) in (3.30) are given by the following system of equations

$$\begin{aligned} \frac{\partial \Pi_i}{\partial q_i^s} &= \frac{\partial}{\partial q_i^s} \alpha_i \beta_j (\gamma - q_i^s - c_i^o - a) q_i^s \\ \frac{\partial \Pi_i}{\partial \tilde{q}_i^s} &= \frac{\partial}{\partial \tilde{q}_i^s} \alpha_j \beta_i (\gamma - \tilde{q}_i^s - c_i^o - b) \tilde{q}_i^s \end{aligned}$$

which gives the solution of the problem:

$$\begin{aligned}(q_i^s)^* &= \frac{\gamma - c_i^o - a}{2} \\ (\tilde{q}_i^s)^* &= \frac{\gamma - c_i^o - b}{2}\end{aligned} \tag{3.33}$$

The profit-maximizing prices are calculated as follows

$$\begin{aligned}(p_i^s)^* &= \frac{\gamma + c_i^o + a}{2} \\ (\tilde{p}_i^s)^* &= \frac{\gamma + c_i^o + b}{2}\end{aligned} \tag{3.34}$$

Notice that the prices for originating traffic are increasing functions in costs and access charges. By substituting (3.34) in (3.28) and (3.29), the optimal prices are given by

$$p_i^s = \begin{cases} \frac{\gamma+c_i^o+a}{2} & \text{if } \frac{\gamma+c_i^o+a}{2} \geq \tilde{p}_j^r \\ \tilde{p}_j^r & \text{if } \frac{\gamma+c_i^o+a}{2} \leq \tilde{p}_j^r \end{cases} \tag{3.35}$$

$$\tilde{p}_i^s = \begin{cases} \frac{\gamma+c_i^o+b}{2} & \text{if } \frac{\gamma+c_i^o+b}{2} \geq p_j^r \\ p_j^r & \text{if } \frac{\gamma+c_i^o+b}{2} \leq p_j^r \end{cases} \tag{3.36}$$

It is straightforward to show that the first-order conditions, which determine the prices for terminating traffic, are equal to a perceived marginal cost and are defined as follows

$$\tilde{p}_i^r = c_i^t - a \tag{3.37}$$

$$p_i^r = c_i^t - b \tag{3.38}$$

Substituting the optimal demands in (3.28), the profit function of ISP$_i$ can be rewritten

$$\begin{aligned}\Pi_i &= \alpha_i\beta_j(\gamma - p_i^s)(p_i^s - c_i^o - a) + \alpha_j\beta_i(\gamma - \tilde{p}_i^s)(\tilde{p}_i^s - c_i^o - b) \\ &\quad + \alpha_j\beta_i(\gamma - p_j^s)(\tilde{p}_i^r + a - c_i^t) + \alpha_i\beta_j(\gamma - \tilde{p}_j^s)(p_i^r + b - c_i^t)\end{aligned}$$

The outcome of the network according to the Nash bargaining game (where providers equally split their payoffs) is defined by

$$\Pi^{NBS} = 0.5(\Pi_i + \Pi_j)$$

If $\Pi_i > \Pi_j$, then ISP$_j$ receives net interconnection payments from ISP$_i$ that is

$$\begin{aligned}\Pi^{NBS} - \Pi_j = 0.5(\Pi_i - \Pi_j) &= 0.5\Delta\sigma \\ &+ 0.5\left[\alpha_i\beta_j(\gamma - p_i^s)(p_i^s - c_i^o - a) - \alpha_j\beta_i(\gamma - p_j^s)(p_j^s - c_j^o - a)\right] \\ &+ 0.5\left[\alpha_j\beta_i(\gamma - \tilde{p}_i^s)(\tilde{p}_i^s - c_i^o - b) - \alpha_i\beta_j(\gamma - \tilde{p}_j^s)(\tilde{p}_j^s - c_j^o - b)\right]\end{aligned} \tag{3.39}$$

Replacing the obtained prices in expression (3.39), the net interconnection charge can be rewritten as follows

$$0.5(\Pi_i - \Pi_j) = 0.5\left[\alpha_i\beta_j\left(\frac{\gamma - c_i^o - a}{2}\right)^2 - \alpha_j\beta_i\left(\frac{\gamma - c_j^o - a}{2}\right)^2\right] + 0.5\left[\alpha_j\beta_i\left(\frac{\gamma - c_i^o - b}{2}\right)^2 - \alpha_i\beta_j\left(\frac{\gamma - c_j^o - b}{2}\right)^2\right] \tag{3.40}$$

In the DTIA model, the net interconnection payment is considered as two independent components i) one for a native traffic business, which is denoted by σ_{ij}^{nat}, and ii) another for a stranger traffic business that is denoted by σ_{ij}^{str}. Then

$$\sigma_{ij}^{nat} = 0.5\left[\alpha_i\beta_j\left(\frac{\gamma - c_i^o - a}{2}\right)^2 - \alpha_j\beta_i\left(\frac{\gamma - c_j^o - a}{2}\right)^2\right] \tag{3.41}$$

$$\sigma_{ij}^{str} = 0.5\left[\alpha_j\beta_i\left(\frac{\gamma - c_i^o - b}{2}\right)^2 - \alpha_i\beta_j\left(\frac{\gamma - c_j^o - b}{2}\right)^2\right] \tag{3.42}$$

Analogous to the previous studies, the following analyses explore how the interconnection payments depend on the differentiated traffic flows considering all available market states in terms of providers' sizes (i.e., market shares).

Proposition 3.14. *If $\alpha_i = \alpha_j$ and $\beta_i = \beta_j$, then net interconnection payments between providers are zero.*

Proof. Given that the networks are symmetric in terms of size, then $c_i^t = c_j^t$. Considering the conditions (3.41) and (3.42), it is straightforward to show that $\sigma_{ij}^{nat} = \sigma_{ij}^{str} = 0$. □

Proposition 3.15. *If $\alpha_i = \alpha_j$ and $\beta_i > \beta_j$, then ISP$_i$ subsidizes ISP$_j$ for stranger traffic.*

Proof. If $\alpha_i = \alpha_j$ and $\beta_i > \beta_j$, then $c_i^t < c_j^t$, $\alpha_i\beta_j < \alpha_j\beta_i$ and $a = c_i^t$.
Native: Considering the native traffic business, where $(\gamma - c_i^o - a) > (\gamma - c_j^o - a)$, the condition (3.41) is not straightforward and is given by

$$\sigma_{ij}^{nat}\begin{cases} > 0 & \text{if } \alpha_i\beta_j/\alpha_j\beta_i > (\gamma - c_j^o - a)^2/(\gamma - c_i^o - a)^2 \\ = 0 & \text{if } \alpha_i\beta_j/\alpha_j\beta_i = (\gamma - c_j^o - a)^2/(\gamma - c_i^o - a)^2 \\ < 0 & \text{if } \alpha_i\beta_j/\alpha_j\beta_i < (\gamma - c_j^o - a)^2/(\gamma - c_i^o - a)^2 \end{cases} \tag{3.43}$$

Stranger: Using (3.42), where $(\gamma - c_i^o - b) > (\gamma - c_j^o - b)$, the stranger traffic component is given by $\sigma_{ij}^{str} > 0$. In this case, ISP$_j$ receives net payments from ISP$_i$. □

Proposition 3.16. *If $\alpha_i > \alpha_j$ and $\beta_i = \beta_j$, then ISP$_i$ subsidizes ISP$_j$ for native traffic.*

Proof. From the definition follows that $c_i^t < c_j^t$, $\alpha_i\beta_j > \alpha_j\beta_i$, and $a = c_i^t$.
Native: Considering the condition (3.41), it can be obtained that $\sigma_{ij}^{nat} > 0$. Here, ISP$_i$ gets higher profit than ISP$_j$ from native traffic exchange and consequently subsidizes the peered network.
Stranger: The expression for stranger traffic business (3.42) is not straightforward and is defined by

$$\sigma_{ij}^{str} \begin{cases} > 0 & \text{if } \alpha_j\beta_i > \alpha_i\beta_j > (\gamma - c_j^o - b)^2/(\gamma - c_i^o - b)^2 \\ = 0 & \text{if } \alpha_j\beta_i > \alpha_i\beta_j = (\gamma - c_j^o - b)^2/(\gamma - c_i^o - b)^2 \\ < 0 & \text{if } \alpha_j\beta_i > \alpha_i\beta_j < (\gamma - c_j^o - b)^2/(\gamma - c_i^o - b)^2 \end{cases} \qquad (\gamma - c_i^o - b) \neq 0 \tag{3.44}$$

□

Assuming that $\alpha_i > \alpha_j$ and $\beta_i > \beta_j$, the following cases for the traffic volumes are obtained from the conditions (3.25) and (3.26): 1) $t_{ij} > t_{ji}$, 2) $t_{ij} < t_{ji}$, and 3) $t_{ij} = t_{ji}$. The cases 1) and 2) are analogous to those described above. We investigate the case when the providers' demands are equal.

Proposition 3.17. *If $\alpha_i > \alpha_j$, $\beta_i > \beta_j$, and $t_{ij} = t_{ji}$, then $\alpha_i > \beta_i$ and $\beta_j > \alpha_j$.*

Proof. The result is obtained from the conditions (3.39) and (3.40)

$$\alpha_i\beta_j\left(\frac{\gamma - c_i^o - a}{2}\right) + \alpha_j\beta_i\left(\frac{\gamma - c_i^o - b}{2}\right) = \alpha_j\beta_i\left(\frac{\gamma - c_j^o - a}{2}\right) + \alpha_i\beta_j\left(\frac{\gamma - c_j^o - b}{2}\right)$$

which gives

$$\frac{\alpha_i\beta_j}{\alpha_j\beta_i} = \frac{a - b + c_j^o - c_i^o}{a - b + c_i^o - c_j^o}$$

Since $c_i^t < c_j^t$, it can be obtained that $(a - b + (c_j^o - c_i^o)) > (a - b - (c_j^o - c_i^o))$. Hence, $\alpha_i\beta_j > \alpha_j\beta_i$, which implies that $\alpha_i > \beta_i$ and $\beta_j > \alpha_j$. □

Proposition 3.18. *If $\alpha_i > \alpha_j$, $\beta_i > \beta_j$, and $t_{ij} = t_{ji}$, then ISP$_i$ subsidizes ISP$_j$ for native traffic.*

Proof. From the definition follows that $a = c_i^t$.
Native: Considering the expression (3.41), it can be obtained that $\sigma_{ij}^{nat} > 0$. Here, under symmetric traffic volumes, ISP$_i$ subsidizes ISP$_j$ for native traffic.
Stranger: The component for the stranger traffic business (3.42) is not straightforward and is defined by (3.44). □

Assuming that $\alpha_i > \alpha_j$ and $\beta_i < \beta_j$, we investigate the case when providers' sizes are symmetric (i.e., $c_i^t = c_j^t$).

Proposition 3.19. *If $\alpha_i > \alpha_j$, $\beta_i < \beta_j$, and $c_i^t = c_j^t$, then ISP$_i$ (ISP$_j$) subsidizes ISP$_j$ (ISP$_i$) for native (stranger) traffic.*

Proof. Symmetry of networks in terms of size implies that $\beta_i = \alpha_j$.
Native: From the condition (3.41) follows that $\sigma_{ij}^{nat} > 0$ and ISP$_i$ subsidizes ISP$_j$.
Stranger: Using the expression for the stranger traffic business (3.42), it can be obtained that $\sigma_{ij}^{str} < 0$. In this case, ISP$_i$ receives net payments from ISP$_j$. □

3.4.3 Non-reciprocal Access Charges

This subsection explores how the profits of providers depend on the differentiated traffic flows considering a market with non-reciprocal access charges. Let a_i and b_i be network i's access charges for terminating native and stranger traffic respectively, where $a_i > b_i$. To carry out our analysis, we follow the assumptions provided for the studies of the inelastic demand model in Section 3.3. In particular, the access charge for terminating native traffic is set to the termination marginal cost, i.e., $a_i = c_i^t$, and for terminating stranger traffic it is defined by $b_i = \varepsilon a_i$ (given that $0.5 \leq \varepsilon < 1$). To simplify analyses we fix $\varepsilon = 0.5$. The incremental profit of ISP$_i$ obtained from the interconnection is

$$\begin{aligned}\Pi_i = {}& \alpha_i\beta_j(p_i^s - c_i^o - a_j)q_i^s + \alpha_j\beta_i(\tilde{p}_i^s - c_i^o - b_j)\tilde{q}_i^s \\ & + \alpha_j\beta_i(\tilde{p}_i^r + a_i - c_i^t)q_j^s + \alpha_i\beta_j(p_i^r + b_i - c_i^t)\tilde{q}_j^s\end{aligned}$$

Retail Prices

Similar to the studies provided for the symmetric access charges, the first-order conditions for profit maximization gives the following system of equations

$$p_i^s = \begin{cases} \frac{\gamma + c_i^o + a_j}{2} & \text{if } \frac{\gamma + c_i^o + a_j}{2} \geq \tilde{p}_j^r \\ \tilde{p}_j^r & \text{if } \frac{\gamma + c_i^o + a_j}{2} \leq \tilde{p}_j^r \end{cases} \tag{3.45}$$

$$\tilde{p}_i^s = \begin{cases} \frac{\gamma + c_i^o + b_j}{2} & \text{if } \frac{\gamma + c_i^o + b_j}{2} \geq p_j^r \\ p_j^r & \text{if } \frac{\gamma + c_i^o + b_j}{2} \leq p_j^r \end{cases} \tag{3.46}$$

The retail prices for terminating traffic are equal to the perceived marginal costs, and therefore, are defined as follows

$$\tilde{p}_i^r = c_i^t - a_i \tag{3.47}$$

$$p_i^r = c_i^t - b_i \tag{3.48}$$

Following the definition that an individual demand of each consumer (website) of network i is q_i^s ($\tilde{q}_i^s$), the total traffic initiated by the particular type of customers of IPS$_i$ is $\alpha_i q_i^s$ and $\beta_i \tilde{q}_i^s$. The $\beta_j(\alpha_j)$ proportion of the traffic originated by a consumer (a website) of ISP$_i$ goes to ISP$_j$. Hence, using the optimal demand function, the amount of native and stranger traffic from ISP$_i$ to ISP$_j$ is defined by

$$\begin{aligned} t_{ij}^{nat} &= \alpha_i \beta_j \left(\frac{\gamma - c_i^o - a_j}{2} \right) \\ t_{ij}^{str} &= \alpha_j \beta_i \left(\frac{\gamma - c_i^o - b_j}{2} \right) \end{aligned} \tag{3.49}$$

Similarly, $\alpha_j q_j^s$ ($\beta_j \tilde{q}_j^s$) traffic is generated by the consumers (websites) of ISP$_j$, and consequently, a proportion β_i (α_i) is terminated in the peered network. The amount of differentiated traffic flowing from ISP$_j$ to ISP$_i$ can be written as follows

$$\begin{aligned} t_{ji}^{nat} &= \alpha_j \beta_i \left(\frac{\gamma - c_j^o - a_i}{2} \right) \\ t_{ji}^{str} &= \alpha_i \beta_j \left(\frac{\gamma - c_j^o - b_i}{2} \right) \end{aligned} \tag{3.50}$$

If network j's actual outcome is less than an outcome according to NBS, meaning that $\Pi_i > \Pi_j$, then the net interconnection payment from ISP$_i$ to ISP$_j$ is calculated as follows

$$\begin{aligned} \Pi^{NBS} - \Pi_j = 0.5\,(\Pi_i - \Pi_j) & \\ &+ 0.5\left[\alpha_i\beta_j(\gamma - p_i^s)(p_i^s - c_i^o - a_j) - \alpha_j\beta_i(\gamma - p_j^s)(p_j^s - c_j^o - a_i)\right] \\ &+ 0.5\left[\alpha_j\beta_i(\gamma - \tilde{p}_i^s)(\tilde{p}_i^s - c_i^o - b_j) - \alpha_i\beta_j(\gamma - \tilde{p}_j^s)(\tilde{p}_j^s - c_i^o - b_i)\right] \end{aligned}$$

Replacing the profit maximizing prices, the equation above can be rewritten as follows

$$\begin{aligned} 0.5(\Pi_i - \Pi_j) = 0.5 &\left[\alpha_i\beta_j \left(\frac{\gamma - c_i^o - a_j}{2} \right)^2 - \alpha_j\beta_i \left(\frac{\gamma - c_j^o - a_i}{2} \right)^2 \right] \\ + 0.5 &\left[\alpha_j\beta_i \left(\frac{\gamma - c_i^o - b_j}{2} \right)^2 - \alpha_i\beta_j \left(\frac{\gamma - c_j^o - b_i}{2} \right)^2 \right] \end{aligned} \tag{3.51}$$

The net payment consists of profits obtained from the exchange of the differentiated traffic flows. The expression for net interconnection charges is considered as two independent parameters for native and stranger traffic flows, that is

$$\sigma_{ij}^{nat} = 0.5 \left[\alpha_i\beta_j \left(\frac{\gamma - c_i^o - a_j}{2} \right)^2 - \alpha_j\beta_i \left(\frac{\gamma - c_j^o - a_i}{2} \right)^2 \right] \tag{3.52}$$

$$\sigma_{ij}^{str} = 0.5 \left[\alpha_j\beta_i \left(\frac{\gamma - c_i^o - b_j}{2} \right)^2 - \alpha_i\beta_j \left(\frac{\gamma - c_j^o - b_i}{2} \right)^2 \right] \tag{3.53}$$

We now investigate the impact of the transmission initiator on net transfers and provide analytical studies.

Proposition 3.20. *If $\alpha_i = \alpha_j$ and $\beta_i = \beta_j$, then net interconnection payments between providers are zero.*

Proof. Given that providers are symmetric in terms of size, then $c_i^t = c_j^t$, and access charges for native and stranger traffic flows are equal. From the conditions (3.52) and (3.53), it can be obtained that $\sigma_{ij}^{nat} = \sigma_{ij}^{str} = 0$. □

Proposition 3.21. *If $\alpha_i = \alpha_j$ and $\beta_i > \beta_j$, then ISP$_i$ (ISP$_j$) subsidizes ISP$_j$ (ISP$_i$) for stranger (native) traffic.*

Proof. From the definition follows that $c_i^t < c_j^t$ and $\alpha_i\beta_j < \alpha_j\beta_i$.
Native: Considering the condition (3.52), where $(\gamma - c_i^o - a_j) = (\gamma - c_j^o - a_i)$ it follows that $\sigma_{ij}^{nat} < 0$. Here, ISP$_j$ subsidizes ISP$_i$ for native traffic.
Stranger: Given that $(\gamma - c_i^o - b_j) > (\gamma - c_j^o - b_i)$ and the business for stranger traffic (3.53), we obtain that $\sigma_{ij}^{str} > 0$. Thus, ISP$_j$ receives payments from ISP$_i$. □

Proposition 3.22. *If $\beta_i = \beta_j$ and $\alpha_i > \alpha_j$, then ISP$_i$ subsidizes ISP$_j$ for native traffic.*

Proof. Given that $\beta_i = \beta_j$ and $\alpha_i > \alpha_j$, then $c_i^t < c_j^t$ and $\alpha_i\beta_j > \alpha_j\beta_i$.
Native: From the condition (3.52) follows that $\sigma_{ij}^{nat} > 0$. This implies that ISP$_i$ subsidizes ISP$_j$ for native traffic.
Stranger: Considering the business for stranger traffic, the component (3.53) is not straightforward and is defined by

$$\sigma_{ij}^{str} \begin{cases} > 0 & \text{if } \alpha_j\beta_i/\alpha_i\beta_j > (\gamma - c_j^o - b_i)^2/(\gamma - c_i^o - b_j)^2 \\ = 0 & \text{if } \alpha_j\beta_i/\alpha_i\beta_j = (\gamma - c_j^o - b_i)^2/(\gamma - c_i^o - b_j)^2 \\ < 0 & \text{if } \alpha_j\beta_i/\alpha_i\beta_j < (\gamma - c_j^o - b_i)^2/(\gamma - c_i^o - b_j)^2 \end{cases} \qquad (\gamma - c_i^o - b_j) \neq 0 \quad (3.54)$$

□

When $\alpha_i > \alpha_j$ and $\beta_i > \beta_j$, we examine the case of the symmetric demands because the cases such as $t_{ij} > t_{ji}$ and $t_{ij} < t_{ji}$ are similar to those considered above.

Proposition 3.23. *If $\alpha_i > \alpha_j$, $\beta_i > \beta_j$, and $t_{ij} = t_{ji}$, then $\alpha_i > \beta_i$ and $\beta_j > \alpha_j$.*

Proof. The result is obtained from the conditions (3.49) and (3.50)

$$\alpha_i\beta_j\left(\frac{\gamma - c_i^o - a_j}{2}\right) + \alpha_j\beta_i\left(\frac{\gamma - c_i^o - b_j}{2}\right) = \alpha_j\beta_i\left(\frac{\gamma - c_j^o - a_i}{2}\right) + \alpha_i\beta_j\left(\frac{\gamma - c_j^o - b_i}{2}\right)$$

which gives

$$\frac{\alpha_i\beta_j}{\alpha_j\beta_i} = \frac{c_j^o - b_j}{c_i^o - b_i}$$

Given that $(c_j^o - b_j) > (c_i^o - b_i)$, it can be easily obtained that $\alpha_i\beta_j > \alpha_j\beta_i$. This gives $\alpha_i > \beta_i$ and $\beta_j > \alpha_j$. □

Proposition 3.24. *If $\alpha_i > \alpha_j$, $\beta_i > \beta_j$, and $t_{ij} = t_{ji}$, then ISP$_i$ subsidizes ISP$_j$ for native traffic.*

Proof. From the definition follows that $c_i^t < c_j^t$.
Native: Considering the native traffic business component (3.52) and result of the Proposition (3.23) that is $\frac{\alpha_i\beta_j}{\alpha_j\beta_i} > 1$, it can be obtained that $\sigma_{ij}^{nat} > 0$. This implies that ISP$_j$ is subsidized by ISP$_i$.
Stranger: The component (3.53) is not straightforward and is defined by (3.54). □

Allowing that $\alpha_i > \alpha_j$ and $\beta_i < \beta_j$, three cases for the termination costs were obtained. However, we investigate the case when providers' sizes are symmetric (i.e., $c_i^t = c_j^t$), because the other forms are similar to those examined above.

Proposition 3.25. *If $\alpha_i > \alpha_j$, $\beta_i < \beta_j$, and $c_i^t = c_j^t$, then ISP$_i$ (ISP$_j$) subsidizes ISP$_j$ (ISP$_i$) for native (stranger) traffic.*

Proof. Symmetry of networks in terms of size implies that $\beta_i = \alpha_j$.
Native: Considering the native traffic component (3.52), it can be obtained that $\sigma_{ij}^{nat} > 0$, and therefore, ISP$_i$ subsidizes ISP$_j$.
Stranger: From the condition (3.53) follows that $\sigma_{ij}^{str} < 0$. In this case, ISP$_i$ receives net payments from ISP$_j$. □

3.4.4 Discussion

The summary of the analytical studies considering markets with reciprocal and non-reciprocal access rates are presented in Tables 3.5-3.9 and Figures 3.3-3.4. The outcomes of the presented models, which show the dependency of the net interconnection payments on the market shares, are presented in Table 3.5. Tables 3.6 and 3.8 report the comparison of the classical model, which performs cost compensation based on the net traffic flows and DTIA in terms of the demand and the NBS outcomes. Tables 3.7 and 3.9 compare retail revenues obtained from the customers, and providers' incremental profits (i.e., obtained from the interconnection). The comparison of providers' outcomes is illustrated in Figures 3.3 and 3.4.

Case	α	β	c^t	**Reciprocal ACs**		**Non-reciprocal ACs**	
				σ^{nat}	σ^{str}	σ^{nat}	σ^{str}
I	$\alpha_i = \alpha_j$	$\beta_i = \beta_j$	$c_i^t = c_j^t$	$\sigma_{ij}^{nat} = 0$	$\sigma_{ij}^{str} = 0$	$\sigma_{ij}^{nat} = 0$	$\sigma_{ij}^{str} = 0$
II	$\alpha_i = \alpha_j$	$\beta_i > \beta_j$	$c_i^t < c_j^t$	eq. (3.43)	$\sigma_{ij}^{str} > 0$	$\sigma_{ij}^{nat} < 0$	$\sigma_{ij}^{str} > 0$
III	$\alpha_i > \alpha_j$	$\beta_i = \beta_j$	$c_i^t < c_j^t$	$\sigma_{ij}^{nat} > 0$	eq. (3.44)	$\sigma_{ij}^{nat} > 0$	eq. (3.54)
IV	$\alpha_i > \alpha_j$	$\beta_i > \beta_j$	$c_i^t < c_j^t$	$\sigma_{ij}^{nat} > 0$	eq. (3.44)	$\sigma_{ij}^{nat} > 0$	eq. (3.54)
	if $t_{ij} = t_{ji}$	$(\alpha_i > \beta_i)$					
V	$\alpha_i > \alpha_j$	$\beta_i < \beta_j$	*if* $c_i^t = c_j^t$	$\sigma_{ij}^{nat} > 0$	$\sigma_{ij}^{str} < 0$	$\sigma_{ij}^{nat} > 0$	$\sigma_{ij}^{str} < 0$
			$(\alpha_j = \beta_i)$				

TABLE 3.5: Interconnection Payments of the DTIA Model with Elastic Demand.

Case	α_i	β_i	t_{ij}		t_{ji}		Π^{NBS}		$\Delta\sigma/2$	
			DTIA	**TF**	**DTIA**	**TF**	**DTIA**	**TF**	**DTIA**	**TF**
I	0.5	0.5	2.06	2.00	2.06	2.00	8.52	8.00	0.00	0.00
II	0.5	0.9	2.11	2.00	1.89	1.88	8.03	7.52	0.90	0.48
	0.5	0.8	2.10	2.00	1.90	1.88	8.03	7.52	0.80	0.48
	0.5	0.7	2.09	2.00	1.91	1.88	8.02	7.52	0.70	0.48
	0.5	0.6	2.08	2.00	1.93	1.88	8.02	7.52	0.60	0.48
III	0.9	0.5	2.01	2.00	1.99	1.88	8.00	7.52	0.10	0.48
	0.8	0.5	2.03	2.00	1.98	1.88	8.01	7.52	0.20	0.48
	0.7	0.5	2.04	2.00	1.96	1.88	8.01	7.52	0.30	0.48
	0.6	0.5	2.05	2.00	1.95	1.88	8.01	7.52	0.40	0.48
IV	0.9	0.8	1.06	1.04	1.02	0.98	4.17	3.91	0.16	0.25
$\alpha_i > \beta_i$	0.8	0.7	1.56	1.52	1.49	1.43	6.09	5.71	0.28	0.37
	0.75	0.65	1.74	1.70	1.66	1.59	6.81	6.39	0.33	0.41
	0.7	0.6	1.89	1.84	1.80	1.73	7.37	6.91	0.36	0.45
V	0.9	0.1	3.28	3.28	3.48	3.28	13.97	13.12	-0.83	0.00
$\alpha_j = \beta_i$	0.8	0.2	2.73	2.72	2.88	2.72	11.58	10.88	-0.62	0.00
	0.7	0.3	2.34	2.32	2.44	2.32	9.88	9.28	-0.41	0.00
	0.6	0.4	2.12	2.08	2.17	2.08	8.86	8.32	-0.21	0.00

TABLE 3.6: Comparison of the DTIA and Classical Model (TF) in Terms of Demand and NBS Outcomes (Reciprocal ACs).

Retail revenues that ISP_i receives from the subscribed consumers and websites present the sum of payments for sending and receiving traffic. They are defined as follows

$$\pi_i(p_i^s, p_i^r) = t_{ij}^{nat} p_i^s + t_{ji}^{str} p_i^r \tag{3.55}$$

$$\tilde{\pi}_i(\tilde{p}_i^s, \tilde{p}_i^r) = t_{ij}^{str} \tilde{p}_i^s + t_{ji}^{nat} \tilde{p}_i^r \tag{3.56}$$

	$\pi_i(p_i^s, p_i^r)$		$\tilde{\pi}_i(\tilde{p}_i^s, \tilde{p}_i^r)$		Π_i		$\pi_j(p_j^s, p_j^r)$		$\tilde{\pi}_j(\tilde{p}_j^s, \tilde{p}_j^r)$		Π_j	
	DTIA	**TF**	**DTIA**	**TF**	**DTIA**	**TF**	**DTIA**	**TF**	**DTIA**	**TF**	**DTIA**	**TF**
I	6.53	6.00	6.11	6.00	8.52	8.00	6.53	6.00	6.11	6.00	8.52	8.00
II	1.30	1.20	11.00	10.80	8.93	8.00	12.46	11.45	1.30	1.27	7.13	7.03
	2.60	2.40	9.78	9.60	8.83	8.00	11.08	10.18	2.60	2.54	7.23	7.03
	3.90	3.60	8.55	8.40	8.72	8.00	9.69	8.90	3.90	3.82	7.32	7.03
	5.20	4.80	7.33	7.20	8.62	8.00	8.31	7.63	5.20	5.09	7.42	7.03
III	11.70	10.80	1.22	1.20	8.10	8.00	1.38	1.27	11.70	11.45	7.90	7.03
	10.40	9.60	2.44	2.40	8.21	8.00	2.77	2.54	10.40	10.18	7.81	7.03
	9.10	8.40	3.67	3.60	8.31	8.00	4.15	3.82	9.10	8.90	7.71	7.03
	7.80	7.20	4.89	4.80	8.41	8.00	5.54	5.09	7.80	7.63	7.61	7.03
IV	4.68	4.32	1.96	1.92	4.33	4.16	2.22	2.04	4.68	4.58	4.01	3.66
	6.24	5.76	3.42	3.36	6.37	6.08	3.88	3.56	6.24	6.11	5.81	5.34
	6.83	6.30	3.97	3.90	7.14	6.80	4.50	4.13	6.83	6.68	6.49	5.98
	7.28	6.72	4.40	4.32	7.73	7.36	4.98	4.58	7.28	7.12	7.01	6.47
V	21.16	19.44	0.24	0.24	13.14	13.12	0.26	0.24	19.79	19.44	14.79	13.12
	16.72	15.36	0.98	0.96	10.96	10.88	1.05	0.96	15.64	15.36	12.20	10.88
	12.80	11.76	2.20	2.16	9.47	9.28	2.35	2.16	11.97	11.76	10.29	9.28
	9.41	8.64	3.91	3.84	8.65	8.32	4.18	3.84	8.80	8.64	9.06	8.32

Table 3.7: Profit Comparison of the Agreements Based on the Net Traffic Flow and DT Flows Compensations (Reciprocal ACs).

Case	α_i	β_i	t_{ij}		t_{ji}		Π^{NBS}		$\Delta\sigma/2$	
			DTIA	**TF**	**DTIA**	**TF**	**DTIA**	**TF**	**DTIA**	**TF**
I	0.5	0.5	2.06	2.00	2.06	2.00	8.52	8.00	0.00	0.00
II	0.5	0.9	2.04	1.88	1.89	1.88	7.74	7.03	0.76	0.00
	0.5	0.8	2.03	1.88	1.90	1.88	7.72	7.03	0.64	0.00
	0.5	0.7	2.01	1.88	1.91	1.88	7.69	7.03	0.53	0.00
	0.5	0.6	1.99	1.88	1.93	1.88	7.67	7.03	0.42	0.00
III	0.9	0.5	1.89	1.88	1.99	1.88	7.54	7.03	-0.14	0.00
	0.8	0.5	1.91	1.88	1.98	1.88	7.57	7.03	-0.03	0.00
	0.7	0.5	1.93	1.88	1.96	1.88	7.59	7.03	0.09	0.00
	0.6	0.5	1.95	1.88	1.95	1.88	7.62	7.03	0.20	0.00
IV	0.9	0.8	1.01	0.98	1.02	0.98	3.95	3.66	0.05	0.00
$\alpha_i > \beta_i$	0.8	0.7	1.48	1.43	1.49	1.43	5.78	5.34	0.12	0.00
	0.75	0.65	1.65	1.59	1.66	1.59	6.47	5.98	0.15	0.00
	0.7	0.6	1.79	1.73	1.80	1.73	7.01	6.47	0.17	0.00
V	0.9	0.1	3.28	3.28	3.48	3.28	13.97	13.12	-0.83	0.00
$\alpha_j = \beta_i$	0.8	0.2	2.73	2.72	2.88	2.72	11.58	10.88	-0.62	0.00
	0.7	0.3	2.34	2.32	2.44	2.32	9.88	9.28	-0.41	0.00
	0.6	0.4	2.12	2.08	2.17	2.08	8.86	8.32	-0.21	0.00

Table 3.8: Comparison of the DTIA and Classical Model (TF) in Terms of Demand and NBS Outcomes (Non-reciprocal ACs).

	$\pi_i(p_i^s, p_i^r)$		$\tilde{\pi}_i(\tilde{p}_i^s, \tilde{p}_i^r)$		Π_i		$\pi_j(p_j^s, p_j^r)$		$\tilde{\pi}_j(\tilde{p}_j^s, \tilde{p}_j^r)$		Π_j	
	DTIA	**TF**	**DTIA**	**TF**	**DTIA**	**TF**	**DTIA**	**TF**	**DTIA**	**TF**	**DTIA**	**TF**
I	6.53	6.00	6.11	6.00	8.52	8.00	6.53	6.00	6.11	6.00	8.52	8.00
II	1.27	1.17	10.91	10.55	8.36	7.03	11.94	10.55	1.20	1.17	7.13	7.03
	2.54	2.34	9.69	9.38	8.21	7.03	10.61	9.38	2.40	2.34	7.23	7.03
	3.82	3.52	8.48	8.20	8.06	7.03	9.29	8.20	3.60	3.52	7.32	7.03
	5.09	4.69	7.27	7.03	7.92	7.03	7.96	7.03	4.80	4.69	7.42	7.03
III	11.45	10.55	1.21	1.17	7.18	7.03	1.33	1.17	10.80	10.55	7.90	7.03
	10.18	9.38	2.42	2.34	7.33	7.03	2.65	2.34	9.60	9.38	7.81	7.03
	8.90	8.20	3.64	3.52	7.47	7.03	3.98	3.52	8.40	8.20	7.71	7.03
	7.63	7.03	4.85	4.69	7.62	7.03	5.31	4.69	7.20	7.03	7.61	7.03
IV	4.58	4.22	1.94	1.88	3.89	3.66	2.12	1.88	4.32	4.22	4.01	3.66
	6.11	5.63	3.39	3.28	5.76	5.34	3.71	3.28	5.76	5.63	5.81	5.34
	6.68	6.15	3.94	3.81	6.46	5.98	4.31	3.81	6.30	6.15	6.49	5.98
	7.12	6.56	4.36	4.22	7.00	6.47	4.78	4.22	6.72	6.56	7.01	6.47
V	21.16	19.44	0.24	0.24	13.14	13.12	0.26	0.24	19.79	19.44	14.79	13.12
	16.72	15.36	0.98	0.96	10.96	10.88	1.05	0.96	15.64	15.36	12.20	10.88
	12.80	11.76	2.20	2.16	9.47	9.28	2.35	2.16	11.97	11.76	10.29	9.28
	9.41	8.64	3.91	3.84	8.65	8.32	4.18	3.84	8.80	8.64	9.06	8.32

TABLE 3.9: Profit Comparison of the Agreements Based on the Net Traffic Flow and DT Flows Compensations (Non-reciprocal ACs).

In the classical model with symmetric access charges, provider i's retail prices that maximize profit are given by

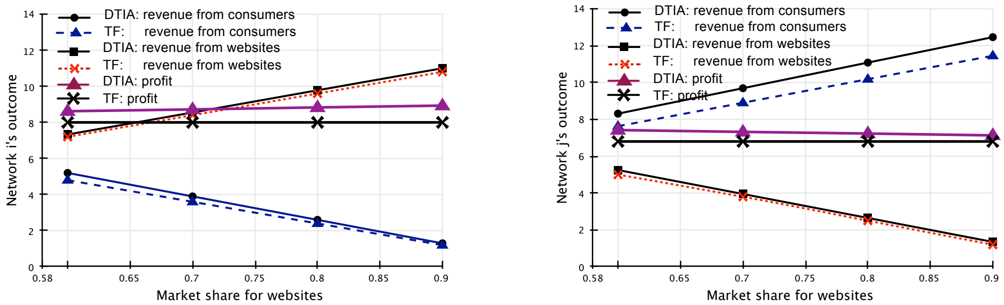
$$p_i^s = \tilde{p}_i^s = \frac{\gamma + c_i^o + a}{2} \qquad p_i^r = \tilde{p}_i^r = c_i^t - a$$

and with asymmetric access rates are defined by

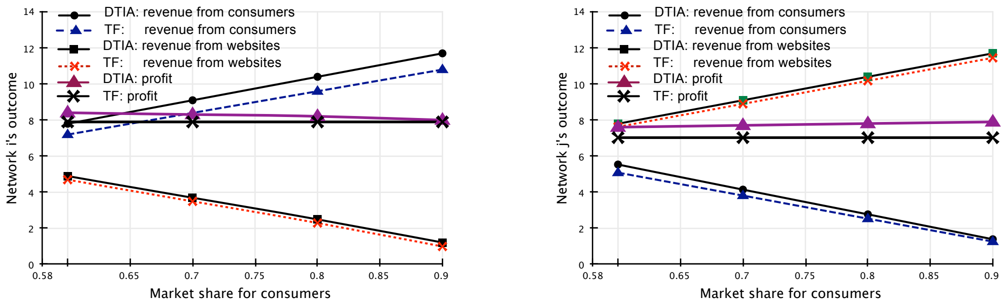
$$p_i^s = \tilde{p}_i^s = \frac{\gamma + c_i^o + a_j}{2} \qquad p_i^r = \tilde{p}_i^r = c_i^t - a_i$$

In order to enable us to calculate specific outcomes, the following values of termination costs were imposed i) $c_i^t = c_j^t = 1$ in cases I and V, ii) $c_i^t = 1$, $c_j^t = 1.5$ in all other cases. The demand is given by $q_i(p_i) = 10 - p_i$. It is important to note that, even though the parameters are chosen arbitrarily, our conclusions do not depend on the chosen parameter values (see Table 3.5).

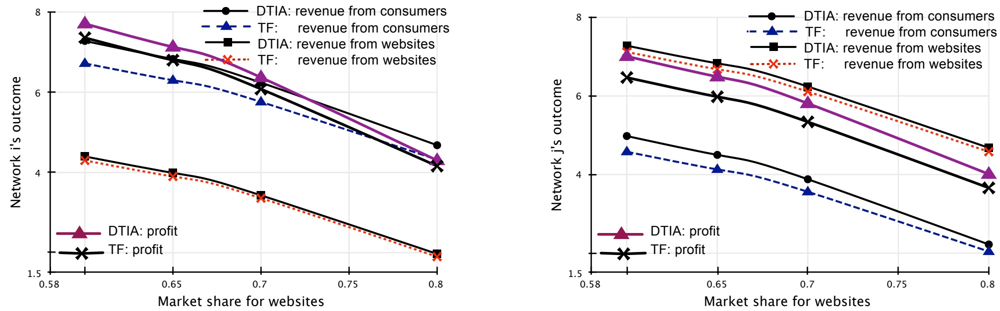
The results obtained from analytical studies indicated that the traffic differentiation approach performed better (in terms of demand and profits) than the classical solution for both models with symmetric and asymmetric access charges. From the comparison between the DTIA model and the agreement based on the net traffic flow compensation follows that the demand (the amount of traffic originated by the providers) is increased. Specifically, DTIA leads to the increase of the traffic volume originated in one network and ready to be terminated in the peered network. Because the *receiver pays* principle



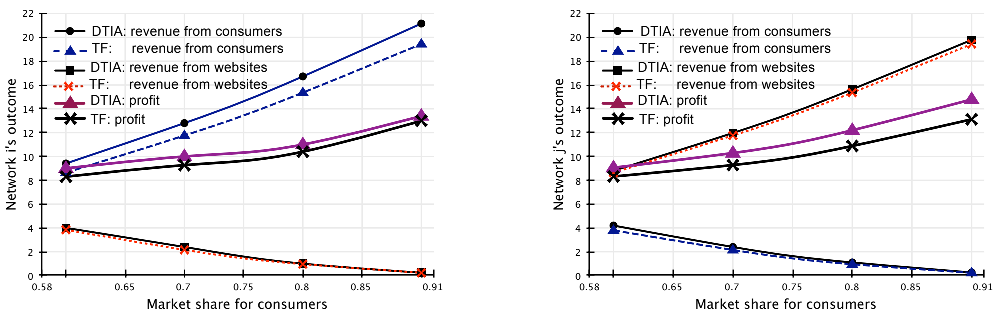
(a) $\alpha_i = \alpha_j$ and $\beta_i > \beta_j$



(b) $\alpha_i > \alpha_j$ and $\beta_i = \beta_j$

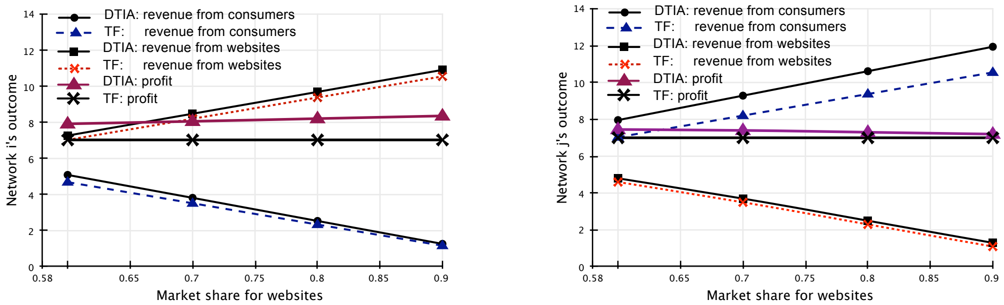


(c) $\alpha_i > \alpha_j$ and $\beta_i > \beta_j$

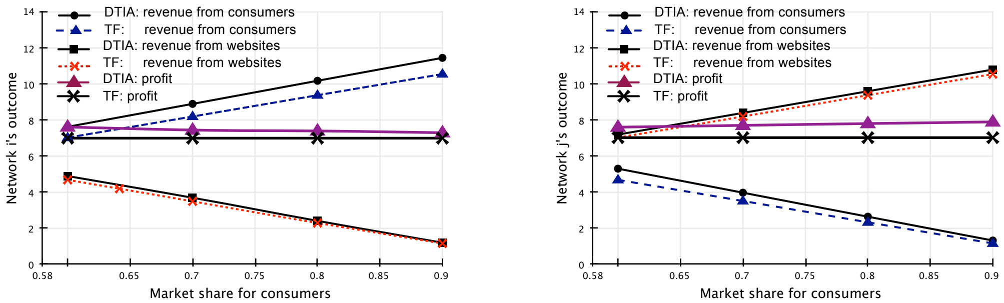


(d) $\alpha_i > \alpha_j$ and $\beta_i < \beta_j$

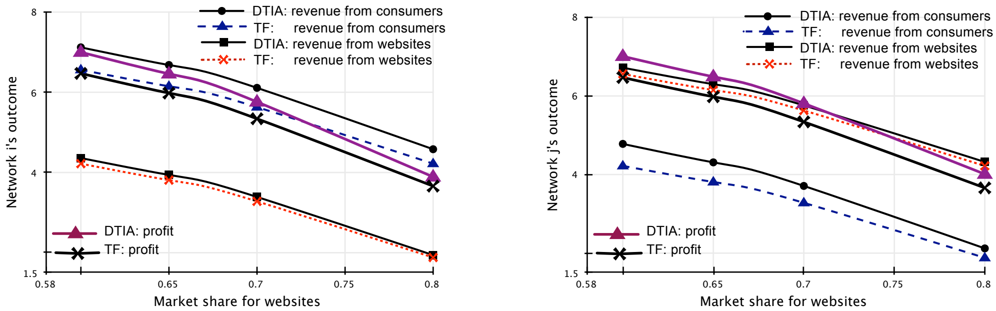
FIGURE 3.3: Comparison of Providers' Outcomes (Reciprocal Access Charges).



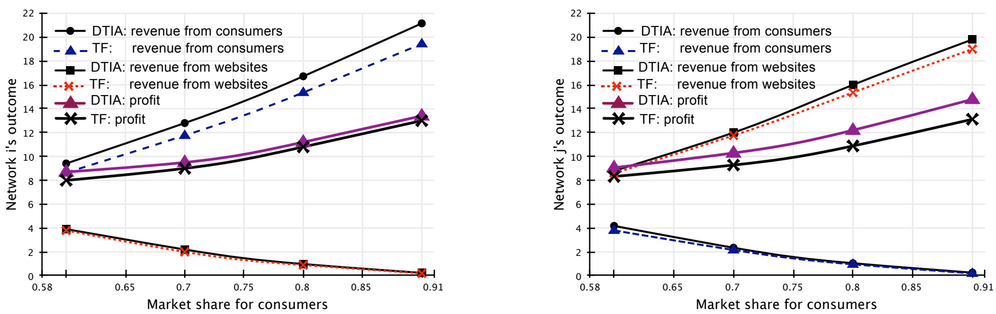
(a) $\alpha_i = \alpha_j$ and $\beta_i > \beta_j$



(b) $\alpha_i > \alpha_j$ and $\beta_i = \beta_j$



(c) $\alpha_i > \alpha_j$ and $\beta_i > \beta_j$



(d) $\alpha_i > \alpha_j$ and $\beta_i < \beta_j$

FIGURE 3.4: Comparison of Providers' Outcomes (Non-reciprocal Access Charges).

was considered, the traffic level originated by any customer depends also on another party which is accepting incoming traffic. This traffic level corresponds to the minimum level that one would like to originate and another would like to accept. In the proposed agreement, the prices obtained for stranger traffic are lower than these prices in the classical model. This is due to the main concept of our strategy, where providers distinguish traffic and compensate the cost for carrying stranger traffic partially. From economics, it is known that the relationship between price and demand is an inverse relationship. This means that a decrease in prices leads to an increase in demand. Obviously, revenues of providers are also increased. More specifically, retail revenues obtained from consumers and websites are higher in DTIA than in the classical model. Finally, the determination of the original initiator of a transmission induces providers to receive higher profits and increases providers' outcomes according to NBS.

3.5 Conclusions

This chapter presented a new inter-provider cost distribution model, called Differentiated Traffic-based Interconnection Agreement (DTIA), considering private peering arrangements. The key idea behind the approach is the determination of the original initiator of a transmission by distinguishing traffic into two types, called native and stranger. In comparison to the existing financial settlement arrangements under which the interconnection payments are based on the net traffic flow, the described model compensates the costs of carrying traffic according to the differentiated traffic flows. More specifically, each provider fully compensates the termination costs incurred from delivering native traffic, which is originally initiated by its own customers, and partially the termination costs incurred from carrying stranger traffic that is originally initiated by the customers of the peered network. The proposed model shares the total interconnection costs between the providers and does not impose any constraints on retail pricing schemes.

A critical challenge in DTIA is determining the original initiator of a transmission in the packet-switched networks. In this work, we have tackled this challenge by marking the information about the transmission initiator in the IP packet header, and have proposed a traffic differentiation mechanism. The main advantage of the presented mechanism is its simplicity that is significant in the Internet. In particular, the provider does not have to maintain a complex identification process of the transmission initiator and to inspect the IP header of packets in order to determine and record all subsequent packets of the transmission. Instead, the defined *membership label* (ML) allows accounting the volume of the appropriate traffic type and therefore leads to low computational complexity.

In order to evaluate the impact of the determination of a transmission initiator on the wholesale and retail markets, we have formulated economic models and analyzed their behaviors. The results indicated that DTIA provides better outcomes than the classical model for both customers and providers. The analyses deal with all available market states in terms of providers market shares.

The following conclusions can be made from the analytical studies, which investigated the inelastic demand model (see Tables 3.1-3.4). They demonstrated that the *symmetry of the costs is not a required prerequisite for peering*, and asymmetric providers can arrange the interconnection without monetary transfers. Further, in contrast to the compensation based on the net traffic flow, the determination of the transmission initiator yields *more fair outcomes for all parties.* And finally, the proposed model outperforms the classical model in terms of the net interconnection payments which are relatively small. This is achieved mainly by the decrease in deviation of the DTIA outcomes from the NBS outcomes. Specifically, our outcomes deviate less from a fair solution than the outcomes of the classical model. Hence, DTIA provides a more fair solution for interconnected providers.

The studies that explored traffic differentiation-based approach considering the elastic demand model concluded that the total demand (the total traffic volume originated by a particular provider) is higher in the proposed scheme than in the classical model (see Tables 3.5-3.9, Figures 3.3-3.4). As a consequence of the demand growth, the retail revenues obtained by the providers are also increased. And finally, the obtained results showed that, in contrast to the net traffic flow based compensation, the consideration of the initiator of a transmission enables providers to obtain greater profits. As a conclusion, the proposed model outperforms the classical model in terms of the profits which are remarkably high.

Chapter 4

Differentiated Traffic-based Interconnection Agreement for Transit Arrangements

"Everything should be made as simple as possible, but not simpler."

Albert Einstein

The objective of this section is to extend the DTIA model and its traffic management mechanism for transit arrangements. Section 4.1 presents the traffic differentiation mechanism that satisfies the scalability criterion. It describes the defined functionalities to support traffic differentiation. In order to evaluate the proposed approach, Sections 4.2 to 4.4 present economic models and their analytical studies. More specifically, Section 4.2 explores the effect of traffic differentiation on the payments of *customer providers*. Following that, Section 4.3 investigates how attractive the DTIA model is to the *providers of different layers*. And finally, Section 4.4 aims to analyze economic efficiency of the market that improves *social welfare*. The conclusions are reported in Section 4.5.

4.1 Traffic Management Mechanism

In the following we propose the traffic management mechanism for interconnection arrangements, which allows recognizing the packet type throughout the network. Unlike the mechanism presented in Chapter 3 which considered only two providers, this mechanism examines transit arrangements and therefore, must be scalable. The key aspect of the proposed mechanism is the identification the type of traffic based on a *two-bit field* in the IP packet header, referred to as the *Membership Label (ML)*.

Packet Marking by a Transmission Initiator

We assume that all nodes within the network support packet marking, where each node sets the *first bit* of the ML field of a native packet to *'1'* and a packet of stranger traffic to *'0'*. The *assignment of the first bit of the label to '1' is done once* when a node originally initiates a transmission.

A consumer can request a webpage either from a subscribed network or from another network. This implies that a transmission endpoint, such as the destination can belong to the same network as the transmission initiator or to another network. Hence, a packet that appears in the network can be originated either by a local transmission endpoint or by an endpoint located in another network. We distinguish the location of a transmission endpoint (i.e., the originator and the terminator) with respect to the network where the packet appears.

The *second bit* of the label set to *'1'* indicates that an endpoint is local, and *'0'* shows that it is located in another network. The *assignment of the second bit of ML to '1' is done once*, when an endpoint of a transmission originates a packet. Obviously, an original initiator of a transmission sets the ML field to *'11'*. Table 4.1 presents the description of the four available values of the label, which will be discussed later in this section.

Outgoing Packet Re-marking

It is obvious that native traffic with regard to one network is stranger with regard to the other. Hence, it is necessary to differentiate the traffic exchanged between networks. In order to achieve that we distinguish the provider's border nodes which are trust boundaries and maintain a connection with an adjacent network, and refer to them as the *Provider-to-Provider Border (PPB)* nodes. For calculating the *first bit* of the membership label of outgoing traffic, a PPB node performs the XOR logical operation on both bits of the ML label. Obviously, the PPB nodes set the *second bit* to *'0'*. Even though packets within a domain can be marked by any available value of ML, *interdomain traffic* can take on only *'00'* or *'10'* values of the label (i.e., stranger or native traffic originated by a transmission endpoint located in any network).

In addition, in order to carry out intercarrier compensation based on the differentiated traffic (DT) flows, each PPB node keeps two counters (one for inbound and another one for outbound traffic) which *calculate the volume of a particular type of traffic*, i.e., native or stranger *with regard to its network*. The volume of the other type of traffic, e.g., native (stranger) can be easily determined by subtracting the volume of stranger (native) traffic from the total count. Table 4.2(a) demonstrates the logic of the PPB nodes for outgoing packet re-marking and for counting outgoing native traffic.

Values of ML	**Description**
00	Stranger packet, originated by an endpoint located in another network
01	Stranger packet, originated by a local endpoint
10	Native packet, originated by an endpoint located in another network
11	Native packet, originated by a local endpoint

TABLE 4.1: Available Values of the Membership Label Field.

(a) Outgoing Packet Re-marking and Counting.

Input	**Output**	**Counter**
00	*00*	NOP
01	*10*	NOP
10	*10*	NOP
11	*00*	Counter1[a]++

(b) Incoming Packet Re-marking and Counting.

Input	**Output(Counter)**	
	If IP destination address is local	Otherwise
00	*01*(NOP)	*00*(NOP)
10	*11*(Counter2[b]++)	*10*(NOP)

[a] Counter1 shows the current value of the counter for outgoing native traffic.

[b] Counter2 shows the current value of the counter for incoming native traffic.

TABLE 4.2: Packet Re-marking and Counting.

Incoming Packet Re-marking

As mentioned before, a website requested by a consumer can be hosted either by the local network or by another network. As a result, traffic originated by an endpoint of a transmission, can be part of a transmission originally initiated either by the network's customer or by the customer of another network. Therefore, the identification of the type of traffic (i.e., native or stranger) originated by the transmission endpoint is necessary. For *incoming traffic that is destined to the network* (i.e., the IP destination address is local), the PPB nodes perform the NOT logical operation on the *second bit* of the label and do not change the *first bit*.

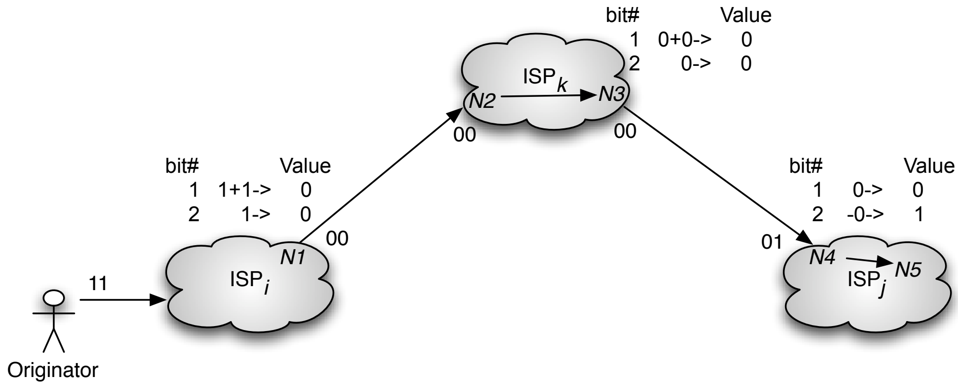
The transmission endpoint does not re-examine the label. It sends *response* packets with the same ML field (i.e., the values *'01'* or *'11'* are copied from the request packet). It is obvious that incoming network traffic with the first bit set to *'1'* and destined to the network is part of a transmission initiated by its own customers. Table 4.2(b) shows the logic of the PPB nodes for incoming traffic and for counting incoming native traffic. An example that helps to understand how the described traffic management mechanism works is described below.

Example

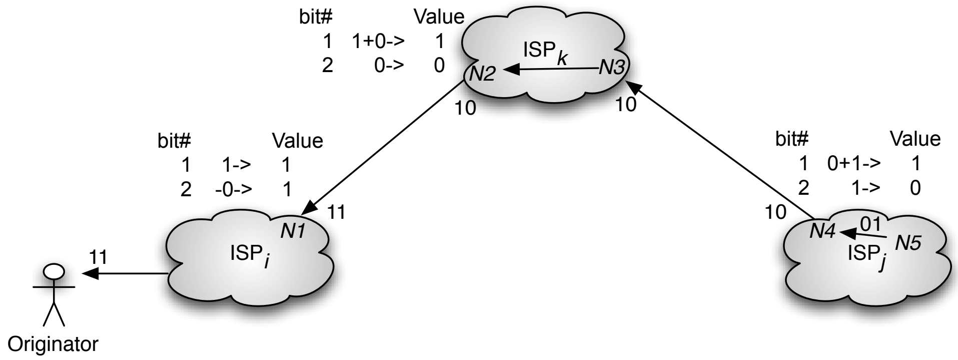
As an example, consider a model consisting of ISP$_i$, ISP$_j$ and their customers as well as the transit network ISP$_k$, where each provider calculates the volumes of native traffic. Assume that a customer of ISP$_i$ requests data available on ISP$_j$. Let *N1* be the PPB node of ISP$_i$, which receives a packet marked by *'11'*. Before forwarding it to ISP$_k$, *N1* performs the XOR operation on the ML field of the outgoing packet (i.e., sets the label to *'00'*), and increases the counter for outgoing native traffic. The PPB node *N2* of ISP$_k$ reads the IP destination address, however does not re-mark the label (since the packet is not destined to its network), and then forwards the packet to PPB node *N3*, which maintains connectivity with ISP$_j$. *N3* node performs the XOR operation on the outgoing packet label (as a result, the ML value remains the same, i.e., *'00'*) and forwards it to PPB node *N4* of ISP$_j$. *N4* node reads the destination IP address, and since the packet is destined for its network, applies the NOT operation on the second bit of the label of the incoming packet (i.e., sets ML to *'01'*) and forwards it to the destination, e.g. the *N5* node (see Figure 4.1(a)). After receiving the packet, *N5* sends a packet stream with the requested data, where the label remains the same (*'01'* i.e., stranger traffic, which is originated locally). The similar procedure follows on the inverse path with only one difference that ISP$_i$ considers the incoming traffic as native, initiated by its own customers. The principle of traffic management mechanism is illustrated in Figure 4.1.

4.1.1 Incentive Compatibility

Although it is out of scope of this thesis to address security issues, this section briefly discusses the desirable property of our mechanism that is incentive compatibility. This implies that strategic agents have no incentive to lie or cheat, i.e., perform untruthful packet marking. In the DTIA model, *customers* have no incentive to cheat if retail prices for differentiated traffic types, such as native and stranger, are equal to each other. We believe that setting different retail prices for each type of traffic is unlikely since it does not effect the quality of service. Moreover, it was shown that customers do not want to be faced with varying prices, which may be difficult to understand [19]. On



(a) Outgoing Packet Re-marking



(b) Incoming Packet Re-marking

FIGURE 4.1: Principle of Traffic Differentiation Mechanism.

the other hand, *providers in DTIA* indeed have an incentive to mark only native packets as stranger in order to reduce the payments.

Unlike the proposed traffic management mechanism, which operates on the network layer of the Open System Interconnection (OSI) model, the proposed security mechanism operates on an upper layer, i.e., the transport layer. It is known that most of the applications run under the TCP or the UDP transport protocols. First, we consider applications running under TCP that is connection-oriented and provide a possible solution. We continue the example above where a customer of ISP$_i$ request data available at ISP$_j$. TCP sockets in a *listening state* are waiting for a connection request from any remote client. In the first step to establish a TCP connection, a client (i.e., a customer of ISP$_i$) sends a TCP packet with the SYN flag set to a server (i.e., a customer of ISP$_j$). At this stage the server receiving the packet tries to establish a connection for the new client. We allow that the TCP pseudo-header (that contains information from the IP header and verifies that a packet has reached the correct destination) also includes the ML information. Before replying to the client, the server checks the IP source address and the ML field. If *the source address is not local and the first bit of the ML field* is set to *'1'* the server simply does not reply. Hence, the client charged by the transit ISP for the request packet, which is marked untruthfully, will not receive a response. Financial loss creates no incentive to cheat. Figure 4.2 outlines the pseudocode of the incentive compatibility mechanism for TCP.

The UDP transport protocol is connectionless, therefore sockets have no states. After receiving a packet, the UDP server (ISP_j) also checks the IP source address and the first bit of the ML field. Now, if *the source address is not local and the packet is marked as native*, this implies that it is the server, i.e., *N5* node of ISP_j which originally initiated this traffic and received a response. Allowing that a node keeps the destination addresses of the initiated transmissions, it can be extracted whether a received packet is native. If a server detects that a packet is marked untruthful, it simply drops it and does not reply. Economically, this creates no incentive to lie or cheat in packet marking. Figure 4.3 outlines the pseudocode of the incentive compatibility mechanism for UDP, where $Initiated = FALSE$ indicates that the UDP server has not originally initiated a particular transmission.

if $(IP\_src \neq local$ and $ML = 11)$ **then**
  drop packet
else
  send SYN/ACK
end if

FIGURE 4.2: Pseudocode of Incentive Compatibility Mechanism for TCP.

if $(IP\_src \neq local$ and $Initiated = FALSE$ and $ML = 11)$ **then**
  drop packet
else
  reply
end if

FIGURE 4.3: Pseudocode of Incentive Compatibility Mechanism for UDP.

4.1.2 Incorporating the ML Label into the IP Header

Incorporation of the defined label in the IP packet header is a matter of finding unused or reserved bits in the header while remaining compatible with the current standards and protocols. To achieve this goal, we propose to use the first two bits of the flags field in the IPv4 header, which implement fragmentation. More specifically, the first bit is reserved and must be zero; the second bit is Don't Fragment (DF). The fragmentation can be avoided if a sender knows the Maximum Transfer Unit (MTU) size of a path to the destination and sends packets whose size is less than the MTU size. In this case the

DF bit can be set to arbitrary value. In the IPv6 header there are more available bits than required to encode the ML field.

4.2 Exploring Payments of Customer Providers

This section extends the analytical studies provided in Chapter 3 and examines transit models. In particular, it explores the role of the DTIA model on net payments of *customer providers* interconnected trough the transit provider. The studies consider both unilateral (where a customer ISP pays to a transit ISP for sent and received traffic) and bilateral (where the payments are based on the net flow of traffic) settlement arrangements.

4.2.1 The Economic Model and its Analyses

We follow the assumption made in the previous chapter in order to capture traffic asymmetry and therefore, consider two types of customers, such as consumers and websites. To capture explicit net transfers between providers in its simplest way, traffic exchange from consumers to websites and from websites to consumers is examined. The studies are provided under the Assumptions 3.2 - 3.4 and the following one:

Assumption 4.1. *Let* $\alpha_i \in (0,1)$ *be network i's market share for consumers and* $\beta_i \in (0,1)$ *its market share for websites. The market consists of only one transit provider and two customer providers,* i *and* j*, where* $i \neq j = 1,2$ *and* $\alpha_i + \alpha_j = 1$*,* $\beta_i + \beta_j = 1$.

We examine a scenario in which ISP_i and ISP_j exchange traffic through the transit provider ISP_k. The amount of the differentiated traffic originating from ISP_i with destination to ISP_j is given by

$$\begin{aligned} t_{ik}^{nat} &= \alpha_i \beta_j N M \\ t_{ik}^{str} &= \alpha_j \beta_i N M x \end{aligned} \tag{4.1}$$

where t_{ik}^{nat} denotes the amount of outgoing *native* traffic (exchanged from consumers to websites) and t_{ik}^{str} is the amount of *stranger* traffic (exchanged from websites to consumers) with respect to ISP_i. The variable x denotes the average amount of traffic requested from a website. Similarly, the differentiated traffic volumes originated by ISP_j and destined to ISP_i are calculated as

$$\begin{aligned} t_{jk}^{nat} &= \alpha_j \beta_i N M \\ t_{jk}^{str} &= \alpha_i \beta_j N M x \end{aligned} \tag{4.2}$$

Here, t_{jk}^{nat} represents the outgoing native traffic and t_{jk}^{str} represents the outgoing stranger traffic with respect to ISP_j. The total amount of traffic originated by ISP_i and ISP_j is

$$t_{ik} = t_{ik}^{nat} + t_{ik}^{str} \tag{4.3}$$

$$t_{jk} = t_{jk}^{nat} + t_{jk}^{str} \tag{4.4}$$

4.2.2 Unilateral Settlement Arrangements

We start by examining unilateral settlement models, in which the transit provider charges the customer providers for every unit of traffic sent and received. Let a_k and b_k be access fees that ISP_k charges customer ISPs for the unit of native and stranger traffic respectively, where $a_k > b_k$ (since the providers compensate partially the costs of carrying stranger traffic). The access charge for the stranger traffic is set $b_k = \varepsilon a_k$, where $0.5 \le \varepsilon < 1$. To simplify our analysis, we set $\varepsilon = 0.5$. The interconnection payments of ISP_i and ISP_j to the transit provider are given by

$$f_{ik} = a_k(t_{ik}^{nat} + t_{jk}^{str}) + b_k(t_{ik}^{str} + t_{jk}^{nat}) \tag{4.5}$$

$$f_{jk} = a_k(t_{jk}^{nat} + t_{ik}^{str}) + b_k(t_{jk}^{str} + t_{ik}^{nat}) \tag{4.6}$$

The sum of these payments represents the incremental revenue of the transit provider obtained from the interconnection, that is

$$\pi_k = f_{ik} + f_{jk}$$

In the DTIA model the interconnection payments of ISP_i and ISP_j are interpreted as two independent components i) one for a native traffic business, and ii) another for a stranger traffic business. These differentiated payments are calculated as follows

$$f_i^{nat} = a_k(t_{ik}^{nat} + t_{jk}^{str}) \qquad f_j^{nat} = a_k(t_{jk}^{nat} + t_{ik}^{str}) \tag{4.7}$$

$$f_i^{str} = b_k(t_{ik}^{str} + t_{jk}^{nat}) \qquad f_j^{str} = b_k(t_{jk}^{str} + t_{ik}^{nat}) \tag{4.8}$$

The following analyses explore how the interconnection payments of the customer providers depend on the determination of a transmission initiator. Analogous to the previous studies, five available market states in terms of relative provider sizes (i.e., market shares) are considered.

Proposition 4.1. *If $\alpha_i = \alpha_j$ and $\beta_i = \beta_j$, then the interconnection charges of customer providers are the same.*

Proof. From the conditions (4.1) and (4.2) follows that $(t_{ik}^{nat} + t_{jk}^{str}) = (t_{ik}^{str} + t_{jk}^{nat})$. As a result, using (4.5)-(4.8), it can be obtained that $f_i^{nat} = f_j^{nat}$, $f_i^{str} = f_j^{str}$ and $f_{ik} = f_{jk}$. □

Proposition 4.2. *If $\alpha_i = \alpha_j$ and $\beta_i > \beta_j$, then the payments of ISP_i are less than the payments of ISP_j.*

Proof. Observing the conditions (4.1) and (4.2), it can be obtained that $(t_{ik}^{nat} + t_{jk}^{str}) < (t_{ik}^{str} + t_{jk}^{nat})$. Therefore, from (4.7) and (4.8) we get that $f_i^{nat} < f_j^{nat}$ and $f_i^{str} > f_j^{str}$. Subtracting expression (4.5) from (4.6) gives that $f_{ik} < f_{jk}$. □

Proposition 4.3. *If $\alpha_i > \alpha_j$ and $\beta_i = \beta_j$, then the payments of ISP_i are higher than the payments of ISP_j.*

Proof. From the conditions (4.1)and (4.2) follows that $(t_{ik}^{nat} + t_{jk}^{str}) > (t_{ik}^{str} + t_{jk}^{nat})$, which gives $f_i^{nat} > f_j^{nat}$, $f_i^{str} < f_j^{str}$. Using 4.5 and 4.6 we obtain that $f_{ik} > f_{jk}$. □

Similar to the previous studies, when $\alpha_i > \alpha_j$ and $\beta_i > \beta_j$, the following cases for the traffic volumes are obtained from the conditions (4.3) and (4.4): 1) $t_{ik} > t_{jk}$, 2) $t_{ik} < t_{jk}$, and 3) $t_{ik} = t_{jk}$. The last case is investigated below since the cases 1) and 2) are analogous to those described above.

Proposition 4.4. *If $\alpha_i > \alpha_j$, $\beta_i > \beta_j$, and $t_{ik} = t_{jk}$, then $\alpha_i = \beta_i$.*

Proof. The result is obtained using conditions (4.3) and (4.4). □

Corollary 4.1. *If $\alpha_i > \alpha_j$, $\beta_i > \beta_j$, and $t_{ik} = t_{jk}$, then $t_{ik}^{nat} = t_{jk}^{nat}$ and $t_{ik}^{str} = t_{jk}^{str}$.*

Proposition 4.5. *If $\alpha_i > \alpha_j$, $\beta_i > \beta_j$, and $t_{ik} = t_{jk}$, then the payments of customer providers are equal, i.e., $f_{ik} = f_{jk}$.*

Proof. The result is obtained from the conditions 4.5 and 4.6 analogous to the previous cases. □

Proposition 4.6. *If $\alpha_i > \alpha_j$ and $\beta_i < \beta_j$, then the payments of ISP_i are higher than the payments of ISP_j.*

Proof. Considering the conditions (4.1) and (4.2) it can be obtained that $(t_{ik}^{nat} + t_{jk}^{str}) > (t_{ik}^{str} + t_{jk}^{nat})$. Consequently, from the expressions (4.5)-(4.8) follows that $f_i^{nat} > f_j^{nat}$, $f_i^{str} < f_j^{str}$, and $f_{ik} > f_{jk}$. □

4.2.3 Bilateral Settlement Arrangements

This subsection formulates bilateral settlement models, in which providers (i.e., transit and customer ISP) get compensated for the costs of carrying traffic. Analytical studies are provided to explore the affect of the determination of a transmission initiator on intercarrier compensation considering arrangements with both reciprocal and non-reciprocal access charges.

4.2.3.1 Reciprocal Access Charges

We examine a model where access charges are set by an industry regulator and then applied reciprocally. Let access fees for every unit of received native and stranger traffic which ISP$_i$ (ISP$_k$) charges ISP$_k$ (ISP$_i$) be denoted by a_i (a_k) and b_i (b_k) respectively, where $a_i > b_i$ ($a_k > b_k$). In the case of symmetric access charges $a_k = a_i = a_j$ and $b_k = b_i = b_j$, where $b_k = \varepsilon a_k$ and $0.5 \leq \varepsilon < 1$ (in our analyses $\varepsilon = 0.5$). The net interconnection payments from ISP$_i$ to the transit provider and vice versa are denoted by f_{ik} and f_{ki} correspondingly

$$f_{ik} = a_k t_{ik}^{nat} + b_k t_{ik}^{str} \tag{4.9}$$

$$f_{ki} = b_k \left(t_{jk}^{nat} + t_{jk}^{str} \right) \tag{4.10}$$

From equation (4.10), it can be noticed that the transit network is charged based on the rate for stranger traffic because we assume that it does not have any customers of its own (Assumption 4.1). Similarly, the net transfers from ISP$_j$ to the transit provider and vice versa are denoted by f_{jk} and f_{kj} respectively

$$f_{jk} = a_k t_{jk}^{nat} + b_k t_{jk}^{str} \tag{4.11}$$

$$f_{kj} = b_k \left(t_{ik}^{nat} + t_{ik}^{str} \right) \tag{4.12}$$

The total interconnection payment and the incremental profit of the transit provider are calculated as follows

$$f_k = f_{ki} + f_{kj} \tag{4.13}$$

$$\pi_k = f_{ik} + f_{jk} - f_k \tag{4.14}$$

where the profit presents the difference between the payments received from and paid to the customer ISPs. The differentiated payments of ISP$_i$ and ISP$_j$ for native and stranger traffic are

$$f_i^{nat} = a_k t_{ik}^{nat} \qquad\qquad f_j^{nat} = a_k t_{jk}^{nat} \tag{4.15}$$

$$f_i^{str} = b_k t_{ik}^{str} \qquad\qquad f_j^{str} = b_k t_{jk}^{str} \tag{4.16}$$

The following lines analyze interconnection payments from the perspective of the customer providers in the DTIA model, considering all available market states.

Proposition 4.7. *If $\alpha_i = \alpha_j$ and $\beta_i = \beta_j$, then the interconnection charges of the customer providers are the same.*

Proof. From the conditions (4.15) and (4.16) follows that $f_i^{nat} = f_j^{nat}$ and $f_i^{str} = f_j^{str}$. Consequently, the payments of providers are equal, that is $f_{ik} = f_{jk}$. □

Proposition 4.8. *If $\alpha_i = \alpha_j$ and $\beta_i > \beta_j$, then the payments of ISP$_i$ are higher than the payments of ISP$_j$.*

Proof. From the equations (4.1) and (4.2) follows that $t_{ik}^{nat} < t_{jk}^{nat}$ and $t_{ik}^{str} > t_{jk}^{str}$. The payment of ISP$_j$ defined by (4.15) for native traffic is higher than that of ISP$_i$, i.e., $f_i^{nat} < f_j^{nat}$. Similarly, we obtain that the payment defined by (4.16) for stranger traffic is higher for ISP$_i$, i.e., $f_i^{str} > f_j^{str}$. By subtracting (4.11) from (4.9) we get $(t_{ik}^{nat} - t_{ij}^{nat})(a_k - b_k x)$. Given that $(a_k - b_k x) < 0$ since $x >> 2$, it can be obtained that $f_{ik} > f_{jk}$. □

Proposition 4.9. *If $\alpha_i > \alpha_j$ and $\beta_i = \beta_j$, then the payments of ISP$_i$ are less than the payments of ISP$_j$.*

Proof. Using the expressions (4.1) and (4.2), it can be obtained that $t_{ik}^{nat} > t_{jk}^{nat}$ and $t_{ik}^{str} < t_{jk}^{str}$. The comparison of the payments defined by (4.15) and (4.16) gives $f_i^{nat} > f_j^{nat}$ and $f_i^{str} < f_j^{str}$. Therefore, from the conditions (4.9) and (4.11) follows that $f_{ik} < f_{jk}$. □

Proposition 4.10. *If $\alpha_i > \alpha_j$, $\beta_i > \beta_j$, and $t_{ik} = t_{jk}$, then the payments of customer providers are equal.*

Proof. Using Proposition (4.4) that gives $\alpha_i = \beta_i$ and the expressions, which define the differentiated payments, it can be obtained that $f_i^{nat} = f_j^{nat}$, $f_i^{str} = f_j^{str}$. Summarizing, $f_{ik} = f_{jk}$. □

Proposition 4.11. *If $\alpha_i > \alpha_j$ and $\beta_i < \beta_j$, then the payments of ISP$_j$ are higher than the payments of ISP$_i$.*

Proof. The structure of the proof is analogous to the proof of Proposition 4.9. That is $f_i^{nat} > f_j^{nat}$, $f_i^{str} < f_j^{str}$, and $f_{ik} < f_{jk}$. □

4.2.3.2 Non-reciprocal Access Charges

This subsection considers that the customer providers set non-reciprocal access charges. The net interconnection payments of transit ISP_k to ISP_i and ISP_j are calculated as

$$f_{ki} = b_i \left(t_{jk}^{nat} + t_{jk}^{str} \right) \tag{4.17}$$

$$f_{kj} = b_j \left(t_{ik}^{nat} + t_{ik}^{str} \right) \tag{4.18}$$

where b_i is the network i's access charge for every unit of received stranger traffic with respect to ISP_k. Similarly, b_j is the network j's access charge. The net transfers from the customer providers to ISP_k are given by the equations (4.9) and (4.11). To carry out analysis, we assume that each customer network's access charge for terminating the native traffic is set to the termination marginal cost, and for terminating the stranger traffic is defined by $b_i = \varepsilon a_i$. We examine the case when the marginal (incremental) costs exhibit increasing returns to scale meaning that the incremental costs of the network decrease as the network size increases.

The further investigation is done similar to the case of reciprocal access charges (see Subsection 4.2.3.1) above. More specifically, the obtained results indicated that the net payments of ISP_i and ISP_j to the transit provider are the same for both DTIA models with symmetric and asymmetric access charges. The only difference is the increase in payments of the transit provider to the customer providers.

4.2.4 Discussion

This subsection analyzes the results of analytical studies which considered both unilateral and bilateral settlement arrangements (see Tables 4.3-4.5). Table 4.3 demonstrates the effect of traffic differentiation on the net payments of the customer providers to the transit provider. The comparison results between the classical transit model and DTIA with unilateral and bilateral settlements are presented in Tables 4.4 and 4.5. For the calculation of specific outcomes, we have assumed the following parameter values: $a_k = 1.5$, $x = 35$, $N = 100$, and $M = 60$. The non-reciprocal access charges of the customer providers are set as follows: i) $a_i = a_j = 0.6$ in case I and ii) $a_i = 0.6$, $a_j = 1$ in all other cases[1]. The parameters are chosen to be reasonable to examine all available

[1] In case V the termination costs of customer providers can be written in one of the forms: $a_i > a_j$, $a_i < a_j$, and $a_i = a_j$.

Case	α	β	t^{nat}	t^{str}	f Unilateral	f Bilateral
I	$\alpha_i = \alpha_j$	$\beta_i = \beta_j$	$t_{ik}^{nat} = t_{jk}^{nat}$	$t_{ik}^{str} = t_{jk}^{str}$	$f_{ik} = f_{jk}$	$f_{ik} = f_{jk}$
II	$\alpha_i = \alpha_j$	$\beta_i > \beta_j$	$t_{ik}^{nat} < t_{jk}^{nat}$	$t_{ik}^{str} > t_{jk}^{str}$	$f_{ik} < f_{jk}$	$f_{ik} > f_{jk}$
III	$\alpha_i > \alpha_j$	$\beta_i = \beta_j$	$t_{ik}^{nat} > t_{jk}^{nat}$	$t_{ik}^{str} < t_{jk}^{str}$	$f_{ik} > f_{jk}$	$f_{ik} < f_{jk}$
IV	$\alpha_i > \alpha_j$	$\beta_i > \beta_j$	*if* $t_{ik}^{nat} = t_{jk}^{nat}$	*if* $t_{ik}^{str} = t_{jk}^{str}$	$f_{ik} = f_{jk}$	$f_{ik} = f_{jk}$
V	$\alpha_i > \alpha_j$	$\beta_i < \beta_j$	$t_{ik}^{nat} > t_{jk}^{nat}$	$t_{ik}^{str} < t_{jk}^{str}$	$f_{ik} > f_{jk}$	$f_{ik} < f_{jk}$

TABLE 4.3: Interconnection Payments of the DTIA Models with Unilateral and Bilateral Settlements.

Case	α_i	β_i	t_{ik}^{nat}	t_{ik}^{str}	t_{jk}^{nat}	t_{jk}^{str}	Unilateral f_{ik}	f_{jk}	f_k	π_k
I	0.5	0.5	1500	52500	1500	52500	121500	121500	0	243000
II	0.5	0.9	300	94500	2700	10500	89100	153900	0	243000
	0.5	0.8	600	84000	2400	21000	97200	145800	0	243000
	0.5	0.7	900	73500	2100	31500	105300	137700	0	243000
	0.5	0.6	1200	63000	1800	42000	113400	129600	0	243000
III	0.9	0.5	2700	10500	300	94500	153900	89100	0	243000
	0.8	0.5	2400	21000	600	84000	145800	97200	0	243000
	0.7	0.5	2100	31500	900	73500	137700	105300	0	243000
	0.6	0.5	1800	42000	1200	63000	129600	113400	0	243000
IV	0.9	0.9	540	18900	540	18900	43740	43740	0	87480
$\alpha_i = \beta_i$	0.8	0.8	960	33600	960	33600	77760	77760	0	155520
	0.7	0.7	1260	44100	1260	44100	102060	102060	0	204120
	0.6	0.6	1440	50400	1440	50400	116640	116640	0	233280
V	0.9	0.2	4320	4200	120	151200	236520	123120	0	359640
	0.8	0.25	3600	10500	300	126000	202500	113400	0	315900
	0.7	0.35	2730	22050	630	95550	164430	107730	0	272160
	0.6	0.4	2160	33600	960	75600	142560	110160	0	252720

TABLE 4.4: Comparative Results of DTIA with Unilateral Settlements.

market states in terms of the providers' market shares. However, the specification is clearly arbitrary. It is important to note that our conclusions do not heavily depend on the chosen parameter values (see Table 4.3). The results obtained for a number of other parameter sets have not produced significant changes.

In the classical model based on the traffic flow compensation, the net interconnection payments of the customer providers and revenue of the transit provider are calculated as follows

$$\check{f}_{ik} = \check{f}_{jk} = a_k(t_{ik} + t_{jk})$$
$$\check{\pi}_k = \check{f}_{ik} + \check{f}_{jk}$$

Case	Classical				Bilateral					
	f_{ik}	f_{jk}	f_k	π_k	f_{ik}	f_{jk}	f_k		π_k	
							DTIA[a]	**DTIA**[b]	**DTIA**[a]	**DTIA**[b]
I	162000	162000	0	324000	41625	41625	81000	2250	32400	50850
II	162000	162000	0	324000	71325	11925	81000	2250	51360	31890
	162000	162000	0	324000	63900	19350	81000	2250	49320	33930
	162000	162000	0	324000	56475	26775	81000	2250	47280	35970
	162000	162000	0	324000	49050	34200	81000	2250	45240	38010
III	162000	162000	0	324000	11925	71325	81000	2250	35040	48210
	162000	162000	0	324000	19350	63900	81000	2250	37080	46170
	162000	162000	0	324000	26775	56475	81000	2250	39120	44130
	162000	162000	0	324000	34200	49050	81000	2250	41160	42090
IV	58320	58320	0	116640	14985	14985	29160	810	15552	14418
	103680	103680	0	207360	26640	26640	51840	1440	27648	25632
	136080	136080	0	272160	34965	34965	68040	1890	36288	33642
	155520	155520	0	311040	39960	39960	77760	2160	41472	38448
V	239760	239760	0	479520	9630	113580	119880	3330	49656	73554
	210600	210600	0	421200	13275	94950	105300	2925	44940	63285
	181440	181440	0	362880	20633	72608	90720	2520	41244	51996
	168480	168480	0	336960	28440	58140	84240	2340	40848	45732

[a] The DTIA model with reciprocal ACs.

[b] The DTIA model with non-reciprocal ACs.

Table 4.5: Comparative Results of DTIA with Bilateral Settlements and the Classical Model with Unilateral Settlements.

The following observation can be made form the obtained results. They showed that in DTIA with unilateral settlements the more outgoing native traffic, the higher costs of the customer ISP (see Table 4.3). This is explained by the higher access charges for native traffic than for stranger traffic. In contrast, in the bilateral settlement model, the costs of the customer ISPs are increased as more traffic is originated. In the classical model with unilateral settlements, the smaller and larger customer providers compensate equally (see Table 4.5). In comparison to this model, both DTIA models with unilateral and bilateral settlements provided unequal and significantly reduced payments of the customer provider (except for case IV, which is the symmetric in terms of traffic volumes and where providers' payments are equal). This is achieved by the main concept of our approach, where providers get compensated differently for traffic originally initiated by their own customers, as opposed to traffic initiated by customers of other networks. Obviously, this results in a decrease in the profits of the transit provider in DTIA, who shares the interconnection costs with other ISPs. Finally, in contrast to the the DTIA and classical models with unilateral settlements, the payments of the transit ISP in DTIA with bilateral settlements are different from zero. As a consequence, the payments of the customer ISPs are lower in DTIA with bilateral settlements than in the other models.

4.3 Exploring Payments of Different Layer Providers

This section extends the analytical studies presented in the previous section and investigates the influence of the determination of a transmission initiator on the interconnection payments of different providers. In particular, a key question addressed here is how attractive the DTIA approach is to different layer providers, such as transit and customer. Unlike the prior reported studies, this section considers customer providers which operate in different cost areas and are charged for connectivity differently. The model structure is similar to the one described in Section 4.2.1.

4.3.1 Unilateral Settlement Arrangements

The investigations begin by examining unilateral settlement arrangements where a transit provider charges customer providers for every unit of traffic sent and received. Let c_i^k and c_j^k be the marginal costs of the connectivity of ISP$_i$ and ISP$_j$ correspondingly. We assume that the providers operate in different cost areas so that $c_i^k < c_j^k$, and the marginal costs exhibit increasing returns to scale (i.e., ISP$_i$ is larger than ISP$_j$). ISP$_k$ charges the customer providers (ISP$_i$ and ISP$_j$) a_k and b_k for every unit of native and stranger traffic respectively, where $a_k > b_k$ (ISPs pay less for stranger traffic). The DTIA is attractive to ISP$_k$ *only if its own costs are covered*. To satisfy this condition we have concluded that in DTIA a customer provider i) compensates fully the imbalance in the connectivity costs between endpoints if the exchanged traffic is native, and ii) does not compensate this difference if the originated traffic is stranger. The difference in the costs of the exchanged traffic between the points is defined by

$$\Delta = c_j^k - c_i^k \tag{4.19}$$

Proposition 4.12. *The access charge for stranger traffic is set to the lowest cost of the connectivity, i.e.,* $b_k = c_i^k$.

Proof. Interconnection costs between the customer providers are covered by the access charges. Since native traffic for ISP$_i$ is stranger for ISP$_j$, the sum of fees for native and stranger traffic is equal to the whole costs of interconnection

$$c_i^k + c_j^k = a_k + b_k \tag{4.20}$$

In the DTIA model, a provider compensates the imbalance in the costs expressed by (4.19) fully only for native traffic. This cost difference is not compensated for the stranger traffic. Consequently, it can be written that

$$a_k = b_k + \Delta \tag{4.21}$$

By substituting (4.19) and (4.21) in (4.20), it can be obtained that the access rate for stranger traffic is set to the lowest cost of the connectivity, that is

$$b_k = c_i^k \tag{4.22}$$

The access charge for native traffic is set to the highest cost of connectivity, that is

$$a_k = c_i^k + \Delta \tag{4.23}$$

□

The interconnection payments of ISP$_i$ and ISP$_j$ are calculated by equations (4.5) and (4.6) correspondingly. Analytical studies carried out for asymmetric providers in terms of size are analogous to the cases II-V in Subsection 4.2.2 and produced the same results. In addition to that, we examine the following case

Proposition 4.13. *If $\alpha_i > \alpha_j$, $\beta_i > \beta_j$, and $t_{ik} < t_{jk}$, then the payments of ISP$_i$ are higher than the payments of ISP$_j$.*

Proof. Given that $t_{ik} < t_{jk}$, from the equations (4.3) and (4.4) we obtain $\alpha_i > \beta_i$ and $\alpha_j < \beta_j$. Using (4.1) and (4.2) follows $(t_{ik}^{nat} + t_{jk}^{str}) > (t_{ik}^{str} + t_{jk}^{nat})$. This gives that $f_i^{nat} > f_j^{nat}$ and $f_i^{str} < f_j^{str}$. By subtracting (4.5) from (4.6) we get that $f_{ik} > f_{jk}$. □

The following lines explore the payments of the customer providers in classical and DTIA models. The net payments of the customer providers according to the traffic flow based compensation are denoted by $\check{f}_{ik}$ and $\check{f}_{jk}$ and are calculated as follows

$$\check{f}_{ik} = c_i^k(t_{ik} + t_{jk}) \tag{4.24}$$
$$\check{f}_{jk} = c_j^k(t_{ik} + t_{jk}) \tag{4.25}$$

Proposition 4.14. *The payment of larger (smaller) providers are higher (less) in DTIA than those in the classical model.*

Proof. Considering the net payments of the larger network ISP$_i$, from the equations (4.5) and (4.24) it follows that $\check{f}_{ik} - f_{ik} = (b_k - a_k)(t_{ik}^{nat} + t_{ij}^{str}) < 0$, i.e., $f_{ik} > \check{f}_{ik}$. Similarly, comparing the net payments of the smaller provider in the DTIA and classical models given by (4.6) and (4.25), it can be obtained that $\check{f}_{jk} - f_{jk} = (a_k - b_k)(t_{ik}^{nat} + t_{ij}^{str}) > 0$. This leads to $f_{jk} < \check{f}_{jk}$. □

4.3.2 Bilateral Settlement Arrangements

This subsection examines bilateral settlement arrangements, under which each provider (including the customer provider) gets compensated for the costs of carrying traffic. Again, the models with reciprocal and non-reciprocal access charges are considered.

4.3.2.1 Reciprocal Access Charges

In the following we explore the case when the customer providers charge the transit provider reciprocal access charges. Let b be the access payment that ISP$_k$ subsidizes ISP$_i$ and ISP$_j$ for every unit of traffic, where $b < c_j^k$. The marginal connectivity costs of the customer providers charged by ISP$_k$ can be written as follows

$$c_i^k + c_j^k = c_k + \sigma \tag{4.26}$$

where c_k is the marginal transportation cost of the transit provider and σ is an arbitrary constant.

Proposition 4.15. *The access charge for stranger traffic set by ISP$_k$ is equal to $b_k = c_k + b$ (i.e., the total costs of ISP$_k$).*

Proof. The network k's costs are comprised of the marginal transmission cost and the payment to access customer provider's infrastructure, i.e., $c_k + b$. The bilateral settlement model is attractive to ISP$_k$ only if its own costs are covered. These costs correspond to the minimum level of access charge set by ISP$_k$, that is

$$c_k + b = \min\{a_k, b_k\}$$

According to the proposed strategy, a provider compensates less the costs of carrying stranger traffic, thus

$$b_k = c_k + b \tag{4.27}$$

Obviously, the access charge for native traffic set by the transit provider is increased by the arbitrary constant and is calculated as follows

$$a_k = b_k + \sigma = c_i^k + c_j^k + b \tag{4.28}$$

□

The net interconnection payments of ISP_i and ISP_j to ISP_k are defined by the equations (4.9) and (4.11), correspondingly. The net transfers of ISP_k to the customer providers are given by

$$f_{ki} = b\left(t_{jk}^{nat} + t_{jk}^{str}\right) \tag{4.29}$$

$$f_{kj} = b\left(t_{ik}^{nat} + t_{ik}^{str}\right) \tag{4.30}$$

The results of the analyses that explored asymmetric providers in terms of sizes where ISP_i is larger than ISP_j, are similar to the results of the cases II-V in Subsection 4.2.3. In addition to that, we examine the following case

Proposition 4.16. *If $\alpha_i > \alpha_j$, $\beta_i > \beta_j$, and $t_{ik} < t_{jk}$, then the payments of ISP_j are higher than the payments of ISP_i.*

Proof. Given that $t_{ik} < t_{jk}$, from the equations (4.3) and (4.4) we obtain $\alpha_i > \beta_i$ and $\alpha_j < \beta_j$. From (4.1) and (4.2) follows $t_{ik}^{nat} > t_{jk}^{nat}$ and $t_{ik}^{str} < t_{jk}^{str}$. This gives that $f_i^{nat} > f_j^{nat}$, $f_i^{str} < f_j^{str}$. By subtracting (4.9) from (4.11) we get that $f_{ik} < f_{jk}$. □

The following lines compare the payments of the customer providers in the DTIA and classical models with bilateral settlements. Before that, we consider access charges and net payments in the classical solution. Let $\check{b}$ be the payment paid by ISP_k to the customer providers for sending traffic. The access charge set by the transit provider, $\check{a}_k$, is defined by

$$\check{a}_k = c_i^k + c_j^k + \check{b} \tag{4.31}$$

Assume that ISP_k has users, therefore b (in DTIA) is the rate charged by the customer providers for every unit of stranger traffic only, while $\check{b}$ (in the classical model) is payment for every unit of traffic. As a result, it can be obtained that $\check{b} \geq b$. The interconnection payments of ISP_i and ISP_j are given by

$$\check{f}_{ik} = \check{a}_k t_{ik} \tag{4.32}$$

$$\check{f}_{jk} = \check{a}_k t_{jk} \tag{4.33}$$

Proposition 4.17. *The net payments of the customer providers in the DTIA model are less than those in the classical model.*

Proof. Considering the payments of ISP_i, from the conditions (4.9) and (4.32) follows

$$\check{f}_{ik} - f_{ik} = t_{ik}^{nat}(\check{a}_k - a_k) + t_{ik}^{str}(\check{a}_k - b_k) > 0 \tag{4.34}$$

Similarly, from the payments of the smaller ISP$_j$ defined by the equations (4.11) and (4.33), it can be obtained that

$$\check{f}_{jk} - f_{jk} = t_{jk}^{nat}(\check{a}_k - a_k) + t_{jk}^{str}(\check{a}_k - b_k) > 0 \tag{4.35}$$

□

4.3.2.2 Non-reciprocal Access Charges

We continue the examination of bilateral settlement arrangements with asymmetric access charges. Let b_i and b_j ($b_i < b_j$) be the access rates for every unit of traffic received by ISP$_i$ and ISP$_j$, correspondingly. Following results of Proposition 4.15, fees that the transit provider charges the customer providers for stranger traffic can be rewritten as

$$b_{ik} = c_k + b_j \tag{4.36}$$

$$b_{jk} = c_k + b_i \tag{4.37}$$

Analogously, the rates for native traffic defined by (4.28) have the following form

$$a_{ik} = b_{ik} + \sigma = c_i^k + c_j^k + b_j \tag{4.38}$$

$$a_{jk} = b_{jk} + \sigma = c_i^k + c_j^k + b_i \tag{4.39}$$

The net interconnection payments from ISP$_i$ to the transit provider and vice versa defined by (4.9) and (4.10) can be rewritten as follows

$$f_{ik} = a_{ik}t_{ik}^{nat} + b_{ik}t_{ik}^{str} \tag{4.40}$$

$$f_{ki} = b_i\left(t_{jk}^{nat} + t_{jk}^{str}\right) \tag{4.41}$$

Similarly, the net transfers from ISP$_j$ to the transit provider and vice versa defined by (4.11) and (4.12) take the following form

$$f_{jk} = a_{jk}t_{jk}^{nat} + b_{jk}t_{jk}^{str} \tag{4.42}$$

$$f_{kj} = b_j\left(t_{ik}^{nat} + t_{ik}^{str}\right) \tag{4.43}$$

We do not report studies that investigate the impact of traffic differentiation on inter-carrier compensation because they are similar to the previous analyses. The obtained results for all cases except the one when $\alpha_i > \alpha_j$, $\beta_i > \beta_j$, and $\alpha_i = \beta_i$ are not straightforward. Instead, the following lines aim to explore the payments of customer ISPs in the classical and DTIA models. For this purpose, we consider access charges and payments in the traffic flow-based compensation model. The access rates that ISP$_k$ charges

ISP$_i$ and ISP$_j$ are

$$\check{a}_{ik} = c_i^k + c_j^k + \check{b}_j \tag{4.44}$$

$$\check{a}_{jk} = c_i^k + c_j^k + \check{b}_i \tag{4.45}$$

where $\check{b}_i$ and $\check{b}_j$ ($\check{b}_i \geq b_i$ and $\check{b}_j \geq b_j$) are access fees set by the customer providers correspondingly. The net payments of the customer providers are given by

$$\check{f}_{ik} = \check{a}_{ik} t_{ik} \tag{4.46}$$

$$\check{f}_{jk} = \check{a}_{jk} t_{jk} \tag{4.47}$$

Proposition 4.18. *The interconnection payments of the customer providers are less in DTIA than those in the classical model.*

Proof. From the payments of ISP$_i$ defined by the equations (4.40) and (4.46) follows

$$\check{f}_{ik} - f_{ik} = t_{ik}^{nat}(\check{a}_{ik} - a_{ik}) + t_{ik}^{str}(\check{a}_{ik} - b_{ik}) > 0 \tag{4.48}$$

Similarly, examining the payments of ISP$_j$ given by (4.41) and (4.47) we get

$$\check{f}_{jk} - f_{jk} = t_{jk}^{nat}(\check{a}_{jk} - a_{jk}) + t_{jk}^{str}(\check{a}_{jk} - b_{jk}) > 0 \tag{4.49}$$

□

4.3.3 Discussion

Tables 4.6-4.10 report the results of analytical studies, which examined how beneficial the determination of a transmission initiator is to the providers of different layers. The comparison results between unilateral settlement models are presented in Table 4.6. Tables 4.7-4.10 demonstrate the comparison between bilateral settlement arrangements with symmetric and asymmetric access charges. The analyses considered all available market states in terms of providers' market shares, where ISP$_i$ is larger than ISP$_j$. The following parameter values were chosen to calculate the specific outcomes: $c_i^k = 0.4$, $c_j^k = 1.5$, $c_k = 0.9$, $b = 0.5$, $b_i = 0.3$, $b_j = 0.5$, $x = 35$, $N = 100$, and $M = 60$. In order to simplify analyses we assume that $\check{b} = b$, $\check{b}_i = b_i$, and $\check{b}_j = b_j$.The parameters are chosen to satisfy the condition that providers operate in different cost areas. However, the specification is clearly arbitrary. It is important to note, that our conclusions do not heavily depend on the chosen parameter values (see Table 4.3, cases II-V; Propositions 4.13-4.14 and 4.16-4.17). The results obtained for a number of other parameter sets have

Case	α_i	β_i	f_i^{nat}	f_j^{nat}	f_{ik}		f_{jk}		π_k	
					DTIA	**TF**	**DTIA**	**TF**	**DTIA**	**TF**
I	0.5	0.9	16200	145800	55080	43200	150120	162000	205200	205200
$\alpha_i = \alpha_j$	0.5	0.8	32400	129600	66960	43200	138240	162000	205200	205200
$\beta_i > \beta_j$	0.5	0.7	48600	113400	78840	43200	126360	162000	205200	205200
	0.5	0.6	64800	97200	90720	43200	114480	162000	205200	205200
II	0.9	0.5	145800	16200	150120	43200	55080	162000	205200	205200
$\alpha_i > \alpha_j$	0.8	0.5	129600	32400	138240	43200	66960	162000	205200	205200
$\beta_i = \beta_j$	0.7	0.5	113400	48600	126360	43200	78840	162000	205200	205200
	0.6	0.5	97200	64800	114480	43200	90720	162000	205200	205200
III	0.9	0.8	58320	25920	65232	22464	41472	84240	106704	106704
$\alpha_i > \alpha_j$	0.8	0.7	77760	45360	89856	32832	66096	123120	155952	155952
$\beta_i > \beta_j$	0.7	0.6	90720	58320	106272	39744	82512	149040	188784	188784
$\alpha_i > \beta_i$	0.6	0.55	87480	71280	106488	42336	94608	158760	201096	201096
IV	0.9	0.9	29160	29160	36936	15552	36936	58320	73872	73872
$\alpha_i > \alpha_j$	0.8	0.8	51840	51840	65664	27648	65664	103680	131328	131328
$\beta_i > \beta_j$	0.7	0.7	68040	68040	86184	36288	86184	136080	172368	172368
$\alpha_i = \beta_i$	0.6	0.6	77760	77760	98496	41472	98496	155520	196992	196992
V	0.9	0.2	233280	6480	235008	63936	68688	239760	303696	303696
$\alpha_i > \alpha_j$	0.8	0.25	194400	16200	198720	56160	68040	210600	266760	266760
$\beta_i < \beta_j$	0.7	0.35	147420	34020	156492	48384	73332	181440	229824	229824
	0.6	0.4	116640	51840	130464	44928	82944	168480	213408	213408

TABLE 4.6: Comparative Results of the Unilateral Settlement Arrangements.

not produced significant changes. Network i's total incremental cost of connectivity represents difference between paid and received payments, that is

$$r_i = f_{ik} - f_{ki}$$

Network k's profit obtained from interconnection is calculated as follows

$$r_k = (f_{ik} + f_{jk}) - (f_{ki} + f_{kj}) = \pi_k - (f_{ki} + f_{kj})$$

where π_k as in the previous section represents the total revenue of ISP$_k$ received from the customer providers.

Comparative results obtained for the arrangements with unilateral settlements (see Table 4.6) demonstrated that in the presented model the payments are decreased for the smaller ISP$_j$ and are increased for the larger ISP$_i$. This is achieved by the different access charges for the distinguished traffic flows. More specifically, the payments of ISP$_i$ are increased due to the native traffic compensation, while the payments of ISP$_j$ are decreased due to the stranger traffic compensation. Further, the results showed that in the proposed model the more outgoing traffic we have the lower are costs of the provider. In particular, incoming and outgoing native traffic are directly proportional. Hence, the network

Case	f_{ik}		f_{jk}		f_{ki}		f_{kj}	
	DTIA	**TF**	**DTIA**	**TF**	**DTIA**	**TF**	**DTIA**	**TF**
I	133020	227520	21180	31680	6600	6600	47400	47400
	119040	203040	35160	56160	11700	11700	42300	42300
	105060	178560	49140	80640	16800	16800	37200	37200
	91080	154080	63120	105120	21900	21900	32100	32100
II	21180	31680	133020	227520	47400	47400	6600	6600
	35160	56160	119040	203040	42300	42300	11700	11700
	49140	80640	105060	178560	37200	37200	16800	16800
	63120	105120	91080	154080	32100	32100	21900	21900
III	26112	42912	54072	91872	19140	19140	8940	8940
	44616	74016	72576	122976	25620	25620	15420	15420
	56952	94752	84912	143712	29940	29940	19740	19740
	68568	114768	82548	139248	29010	29010	23910	23910
IV	27756	46656	27756	46656	9720	9720	9720	9720
	49344	82944	49344	82944	17280	17280	17280	17280
	64764	108864	64764	108864	22680	22680	22680	22680
	74016	124416	74016	124416	25920	25920	25920	25920
V	16248	20448	211968	363168	75660	75660	4260	4260
	23340	33840	177120	303120	63150	63150	7050	7050
	37422	59472	135282	230832	48090	48090	12390	12390
	52224	85824	108144	183744	38280	38280	17880	17880

Table 4.7: Payments Comparison of the Bilateral Settlement Arrangements (Reciprocal ACs).

Case	π_k		r_k		r_i		r_j	
	DTIA	**TF**	**DTIA**	**TF**	**DTIA**	**TF**	**DTIA**	**TF**
I	154200	259200	100200	205200	126420	220920	-26220	-15720
	154200	259200	100200	205200	107340	191340	-7140	13860
	154200	259200	100200	205200	88260	161760	11940	43440
	154200	259200	100200	205200	69180	132180	31020	73020
II	154200	259200	100200	205200	-26220	-15720	126420	220920
	154200	259200	100200	205200	-7140	13860	107340	191340
	154200	259200	100200	205200	11940	43440	88260	161760
	154200	259200	100200	205200	31020	73020	69180	132180
III	80184	134784	52104	106704	6972	23772	45132	82932
	117192	196992	76152	155952	18996	48396	57156	107556
	141864	238464	92184	188784	27012	64812	65172	123972
	151116	254016	98196	201096	39558	85758	58638	115338
IV	55512	93312	36072	73872	18036	36936	18036	36936
	98688	165888	64128	131328	32064	65664	32064	65664
	129528	217728	84168	172368	42084	86184	42084	86184
	148032	248832	96192	196992	48096	98496	48096	98496
V	228216	383616	148296	303696	-59412	-55212	207708	358908
	200460	336960	130260	266760	-39810	-29310	170070	296070
	172704	290304	112224	229824	-10668	11382	122892	218442
	160368	269568	104208	213408	13944	47544	90264	165864

Table 4.8: Comparative Results of the Bilateral Settlement Arrangements (Reciprocal ACs).

Case	f_{ik}		f_{jk}		f_{ki}		f_{kj}	
	DTIA	**TF**	**DTIA**	**TF**	**DTIA**	**TF**	**DTIA**	**TF**
I	133020	227520	18540	29040	3960	3960	47400	47400
	119040	203040	30480	51480	7020	7020	42300	42300
	105060	178560	42420	73920	10080	10080	37200	37200
	91080	154080	54360	96360	13140	13140	32100	32100
II	21180	31680	114060	208560	28440	28440	6600	6600
	35160	56160	102120	186120	25380	25380	11700	11700
	49140	80640	90180	163680	22320	22320	16800	16800
	63120	105120	78240	141240	19260	19260	21900	21900
III	26112	42912	46416	84216	11484	11484	8940	8940
	44616	74016	62328	112728	15372	15372	15420	15420
	56952	94752	72936	131736	17964	17964	19740	19740
	68568	114768	70944	127644	17406	17406	23910	23910
IV	27756	46656	23868	42768	5832	5832	9720	9720
	49344	82944	42432	76032	10368	10368	17280	17280
	64764	108864	55692	99792	13608	13608	22680	22680
	74016	124416	63648	114048	15552	15552	25920	25920
V	16248	20448	181704	332904	45396	45396	4260	4260
	23340	33840	151860	277860	37890	37890	7050	7050
	37422	59472	116046	211596	28854	28854	12390	12390
	52224	85824	92832	168432	22968	22968	17880	17880

TABLE 4.9: Payments Comparison of the Bilateral Settlement Arrangements (Non-reciprocal ACs).

Case	π_k		r_k		r_i		r_j	
	DTIA	**TF**	**DTIA**	**TF**	**DTIA**	**TF**	**DTIA**	**TF**
I	151560	256560	100200	205200	129060	223560	-28860	-18360
	149520	254520	100200	205200	112020	196020	-11820	9180
	147480	252480	100200	205200	94980	168480	5220	36720
	145440	250440	100200	205200	77940	140940	22260	64260
II	135240	240240	100200	205200	-7260	3240	107460	201960
	137280	242280	100200	205200	9780	30780	90420	174420
	139320	244320	100200	205200	26820	58320	73380	146880
	141360	246360	100200	205200	43860	85860	56340	119340
III	72528	127128	52104	106704	14628	31428	37476	75276
	106944	186744	76152	155952	29244	58644	46908	97308
	129888	226488	92184	188784	38988	76788	53196	111996
	139512	242412	98196	201096	51162	97362	47034	103734
IV	51624	89424	36072	73872	21924	40824	14148	33048
	91776	158976	64128	131328	38976	72576	25152	58752
	120456	208656	84168	172368	51156	95256	33012	77112
	137664	238464	96192	196992	58464	108864	37728	88128
V	197952	353352	148296	303696	-29148	-24948	177444	328644
	175200	311700	130260	266760	-14550	-4050	144810	270810
	153468	271068	112224	229824	8568	30618	103656	199206
	145056	254256	104208	213408	29256	62856	74952	150552

TABLE 4.10: Comparative Results of the Bilateral Settlement Arrangements (Non-reciprocal ACs).

that sends more native traffic incurs higher costs than the network that receives this traffic. This is explained by the higher access charges for native traffic than for stranger traffic. The costs of both customer networks are equal only in the case when their native and stranger traffic volumes are symmetric correspondingly. Finally, the results demonstrated that the revenues of the transit provider in the classical model based on the traffic flows compensation and DTIA are equal.

The key consequences provided below are based on the analytical studies, which explored bilateral settlement arrangements with symmetric and asymmetric access fees (see Tables 4.7-4.10). In DTIA, the payments paid by the customer providers are decreased and those of transit provider remain the same (see Tables 4.7 and 4.9). More specifically, providers ISP_i and ISP_j compensate based on the differentiated traffic flows where the access charge for stranger traffic flow is lower than the access charge set in the classical model. As a consequence, the total incremental costs of the customer providers (r_i and r_j) are also decreased (see Tables 4.8 and 4.10). On the other side, profits of ISP_k obtained from the interconnection (i.e., differences between received and paid payments, r_k) are lower than those in the traffic flow-based compensation model. However, as mentioned earlier in Chapter 2, it was argued that compensation in bilateral arrangements cannot be solely done based on traffic flows, which provide a poor basis for the interconnection cost sharing.

The provided studies examined a model consisting of one transit and two customer ISPs. One question that arises here is on the robustness of the obtained results for more realistic scenarios, which consider more transit and customer ISPs. From Propositions 4.14, 4.17 and 4.18, it can be noticed that the results depend only on the access charges of both DTIA and classical models. More specifically, in the unilateral settlement arrangements, the results rely on the inequality $(a_k - b_k) > 0$. Analogously, the results given by (4.34) and (4.35) depend on the inequalities $(\breve{a}_k - a_k) > 0$ and $(\breve{a}_k - b_k) > 0$, while results expressed by (4.48) and (4.49) are based on $(\breve{a}_{ik} - a_{ik}) > 0$ and $(\breve{a}_{ik} - b_{ik}) > 0$. Hence, the provided conclusions remain the same. Obviously, in the extended scenarios, access charges are obtained by solving a system of linear equations.

4.4 Exploring Social Welfare

The objective of this section is to explore the efficiency of traffic differentiation in terms of social welfare. We formulate economic models with bilateral and unilateral settlements and provide analytical studies, which consider the elastic demand model (i.e., customer demands increase or decrease with market price changes). The described models follow Assumptions 3.2, 3.3, 3.5, and 4.1.

4.4.1 Unilateral Settlement Arrangements

This subsection considers a market with unilateral settlements, where customer providers compensate the transit provider for the costs of carrying traffic, and analyzes its social welfare.

Demand Structure

We examine a scenario where ISP$_i$ and ISP$_j$ are interconnected through a transit provider ISP$_k$, and focus on an asymmetric traffic pattern (considering traffic exchange from consumers to websites and vice versa). The demand structure is similar to the structure described in Section 3.4.1. Thus, an individual demand that optimizes the customer's utility is defined by equation (3.21). Let q_i^s and $\tilde{q}_i^s$ be the levels of traffic originated by each consumer and each website of ISP$_i$, respectively. For simplicity, we consider that these demands depend only on the price set by the customer's provider; they do not depend on the receiver price. Thus, they are calculated as follows

$$\begin{aligned} q_i^s &= \gamma - p_i^s \\ \tilde{q}_i^s &= \gamma - \tilde{p}_i^s \end{aligned} \tag{4.50}$$

Similarly, an individual demand of each type of the customers subscribed to ISP$_j$ is

$$\begin{aligned} q_j^s &= \gamma - p_j^s \\ \tilde{q}_j^s &= \gamma - \tilde{p}_j^s \end{aligned} \tag{4.51}$$

The utilities derived by a consumer and a website of ISP$_i$ for sending and receiving traffic are given by

$$U_i = [u(q_i^s) - p_i^s q_i^s] + \left[u(\tilde{q}_j^s) - p_i^r \tilde{q}_j^s\right] \tag{4.52}$$

$$\tilde{U}_i = [u(\tilde{q}_i^s) - \tilde{p}_i^s \tilde{q}_i^s] + \left[u(q_j^s) - \tilde{p}_i^r q_j^s\right] \tag{4.53}$$

where p_i^s and p_i^r ($\tilde{p}_i^s$ and $\tilde{p}_i^r$) are network i's prices that the subscribed consumer (the hosted website) pays for sending and receiving a unit of traffic.

Cost Structure and Profits

Consider the case when ISP$_i$ operates in a low cost area while ISP$_j$ is located in a high cost area. The connectivity cost structure is the same as in the previous section, viz., c_i^k and c_j^k are the marginal costs of connectivity of ISP$_i$ and ISP$_j$, correspondingly. The operation of networks in different cost areas implies that $c_i^k < c_j^k$, i.e., ISP$_i$ is larger than ISP$_j$. Let $c_i^o > 0$ and $c_i^t > 0$ be network i's marginal costs of origination and termination respectively, where $c_i^o = c_i^t$. These costs exhibit increasing returns to scale, meaning that the incremental costs of the network increase as the network size decreases, i.e., $c_i^o < c_j^o$. For simplicity, fixed network costs are neglected. The profits of the customer providers present the sum of profits for sending and receiving traffic and are given by

$$\begin{aligned} \Pi_i \quad &= \alpha_i\beta_j \left(p_i^s - c_i^o - a_k\right) q_i^s + \alpha_j\beta_i \left(\tilde{p}_i^s - c_i^o - b_k\right) \tilde{q}_i^s \\ &+\alpha_j\beta_i \left(\tilde{p}_i^r - c_i^t - b_k\right) q_j^s + \alpha_i\beta_j \left(p_i^r - c_i^t - a_k\right) \tilde{q}_j^s \end{aligned} \tag{4.54}$$

$$\begin{aligned} \Pi_j \quad &= \alpha_j\beta_i \left(p_j^s - c_j^o - a_k\right) q_j^s + \alpha_i\beta_j \left(\tilde{p}_j^s - c_j^o - b_k\right) \tilde{q}_j^s \\ &+\alpha_i\beta_j \left(\tilde{p}_j^r - c_j^t - b_k\right) q_i^s + \alpha_j\beta_i \left(p_j^r - c_j^t - a_k\right) \tilde{q}_i^s \end{aligned} \tag{4.55}$$

where a_k and b_k are access charges set by ISP$_k$ for the distinguished traffic and have the same structure as the rates in Section 4.3.1. Then

$$\begin{aligned} a_k &= c_i^k + \Delta \\ b_k &= c_i^k \end{aligned}$$

The profit of the transit provider comprises of the payments obtained from the customer ISPs and is given by

$$\begin{aligned} \Pi_k \quad &= a_k \left(\alpha_i\beta_j q_i^s + \alpha_i\beta_j \tilde{q}_j^s\right) + b_k \left(\alpha_j\beta_i \tilde{q}_i^s + \alpha_j\beta_i q_j^s\right) \\ &+a_k \left(\alpha_j\beta_i q_j^s + \alpha_j\beta_i \tilde{q}_i^s\right) + b_k \left(\alpha_i\beta_j \tilde{q}_j^s + \alpha_i\beta_j q_i^s\right) \end{aligned} \tag{4.56}$$

Retail Prices

Consider the case when ISP$_i$ and ISP$_j$ maximize their profits, setting retail prices equal to the perceived marginal costs. Hence, the prices for every unit of traffic sent and received by a customer are given by

$$\begin{aligned} p_i^s &= c_i^o + a_k \quad p_j^s = c_j^o + a_k \\ p_i^r &= c_i^t + a_k \quad p_j^r = c_j^t + a_k \end{aligned} \tag{4.57}$$

Similarly, the retail prices for websites are defined by

$$\begin{aligned} \tilde{p}_i^s &= c_i^o + b_k \quad \tilde{p}_j^s = c_j^o + b_k \\ \tilde{p}_i^r &= c_i^t + b_k \quad \tilde{p}_j^r = c_j^t + b_k \end{aligned} \tag{4.58}$$

It can be noticed that the retail prices are increasing functions in costs and access charges.

Social Welfare

Social welfare of the market presents the sum of consumer surplus and provider surplus (i.e., profit), that is

$$W = \alpha_i\beta_j(U_i + \tilde{U}_j) + \alpha_j\beta_i(U_j + \tilde{U}_i) + \Pi_i + \Pi_j + \Pi_k \tag{4.59}$$

Notice that U_i is the utility of a consumer who initiates q_i^s requests where a β_j proportion goes to ISP$_j$. Since we neglected on-net traffic and considered only off-net traffic, therefore, the sum of consumer utilities subscribed to the network i is given by $\alpha_i\beta_j U_i$. Analogously, an α_j proportion of traffic originated by a website of ISP$_i$ is terminated in ISP$_j$. As a result, the total utility generated by websites hosted by the network i is defined by $\alpha_j\beta_i\tilde{U}_i$. Replacing the components of social welfare by their expressions, where $\Pi_i = 0$ and $\Pi_j = 0$ (since the prices are set to the perceived marginal costs), equation (4.59) can be rewritten as follows

$$\begin{aligned}
W = {} & \alpha_i\beta_j((\gamma - 0.5q_i^s)q_i^s - p_i^s q_i^s + (\gamma - 0.5\tilde{q}_j^s)\tilde{q}_j^s - p_i^r\tilde{q}_j^s) \\
& + \alpha_j\beta_i((\gamma - 0.5\tilde{q}_i^s)\tilde{q}_i^s - \tilde{p}_i^s\tilde{q}_i^s + (\gamma - 0.5q_j^s)q_j^s - \tilde{p}_i^r q_j^s) \\
& + \alpha_j\beta_i((\gamma - 0.5q_j^s)q_j^s - p_j^s q_j^s + (\gamma - 0.5\tilde{q}_i^s)\tilde{q}_i^s - p_j^r\tilde{q}_i^s) \\
& + \alpha_i\beta_j((\gamma - 0.5\tilde{q}_j^s)\tilde{q}_j^s - \tilde{p}_j^s\tilde{q}_j^s + (\gamma - 0.5q_i^s)q_i^s - \tilde{p}_j^r q_i^s) \\
& + a_k\left(\alpha_i\beta_j q_i^s + \alpha_i\beta_j\tilde{q}_j^s\right) + b_k\left(\alpha_j\beta_i\tilde{q}_i^s + \alpha_j\beta_i q_j^s\right) \\
& + a_k\left(\alpha_j\beta_i q_j^s + \alpha_j\beta_i\tilde{q}_i^s\right) + b_k\left(\alpha_i\beta_j\tilde{q}_j^s + \alpha_i\beta_j q_i^s\right)
\end{aligned} \tag{4.60}$$

The following lines compare social welfare in the DTIA and classical models, both with unilateral settlements. For that purpose, we consider providers' profits and social welfare in the traffic flow-based compensation model. As defined before c_i^k and c_j^k are fees that ISP$_k$ charges customer ISPs to access its infrastructure. The profits of the customer providers are defined by

$$\begin{aligned}
\check{\Pi}_i \ & = \alpha_i\beta_j\left(P_i^s - c_i^o - c_i^k\right)Q_i^s + \alpha_j\beta_i\left(\tilde{P}_i^s - c_i^o - c_i^k\right)\tilde{Q}_i^s \\
& +\alpha_j\beta_i\left(\tilde{P}_i^r - c_i^t - c_i^k\right)Q_j^s + \alpha_i\beta_j\left(P_i^r - c_i^t - c_i^k\right)\tilde{Q}_j^s
\end{aligned} \tag{4.61}$$

$$\begin{aligned}
\check{\Pi}_j \ & = \alpha_j\beta_i\left(P_j^s - c_j^o - c_j^k\right)Q_j^s + \alpha_i\beta_j\left(\tilde{P}_j^s - c_j^o - c_j^k\right)\tilde{Q}_j^s \\
& +\alpha_i\beta_j\left(\tilde{P}_j^r - c_j^t - c_j^k\right)Q_i^s + \alpha_j\beta_i\left(P_j^r - c_j^t - c_j^k\right)\tilde{Q}_i^s
\end{aligned} \tag{4.62}$$

where P_i, $\tilde{P}_i$ are retail prices set to the perceived marginal costs as in DTIA; Q_i, $\tilde{Q}_i$ denote demand functions calculated similar to equations (4.50) and (4.51). The profit of the transit provider is given by

$$\check{\Pi}_k = (c_i^k + c_j^k)\left(\alpha_i\beta_j Q_i^s + \alpha_j\beta_i\tilde{Q}_i^s + \alpha_j\beta_i Q_j^s + \alpha_i\beta_j\tilde{Q}_j^s\right) \tag{4.63}$$

The social welfare function of the classical model can be written as follows

$$\begin{aligned}\check{W} &= \alpha_i\beta_j((\gamma - 0.5Q_i^s)Q_i^s - P_i^s Q_i^s + (\gamma - 0.5\tilde{Q}_j^s)\tilde{Q}_j^s - P_i^r\tilde{Q}_j^s) \\ &+ \alpha_j\beta_i((\gamma - 0.5\tilde{Q}_i^s)\tilde{Q}_i^s - \tilde{P}_i^s\tilde{Q}_i^s + (\gamma - 0.5Q_j^s)Q_j^s - \tilde{P}_i^r Q_j^s) \\ &+ \alpha_j\beta_i((\gamma - 0.5Q_j^s)Q_j^s - P_j^s Q_j^s + (\gamma - 0.5\tilde{Q}_i^s)\tilde{Q}_i^s - P_j^r\tilde{Q}_i^s) \\ &+ \alpha_i\beta_j((\gamma - 0.5\tilde{Q}_j^s)\tilde{Q}_j^s - \tilde{P}_j^s\tilde{Q}_j^s + (\gamma - 0.5Q_i^s)Q_i^s - \tilde{P}_j^r Q_i^s) \\ &+ (c_i^k + c_j^k)\left(\alpha_i\beta_j Q_i^s + \alpha_j\beta_i\tilde{Q}_i^s + \alpha_j\beta_i Q_j^s + \alpha_i\beta_j\tilde{Q}_j^s\right)\end{aligned} \tag{4.64}$$

Proposition 4.19. *Social welfare in DTIA is higher than that in the classical model.*

Proof. From the comparison of the expressions (4.60) and (4.64) where $\Pi_k = \check{\Pi}_k$ (because the transit provider in both models covers its own costs and as a result, generates the same profits) follows

$$\begin{aligned}W - \check{W} &= \alpha_i\beta_j q_i^s(2\gamma - q_i^s - p_i^s - \tilde{p}_j^r) + \alpha_j\beta_i\tilde{q}_i^s(2\gamma - \tilde{q}_i^s - \tilde{p}_i^s - p_j^r) \\ &+ \alpha_j\beta_i q_j^s(2\gamma - q_j^s - p_j^s - \tilde{p}_i^r) + \alpha_i\beta_j\tilde{q}_j^s(2\gamma - \tilde{q}_j^s - \tilde{p}_j^s - p_i^r) \\ &- \alpha_i\beta_j Q_i^s(2\gamma - Q_i^s - P_i^s - \tilde{P}_j^r) - \alpha_j\beta_i\tilde{Q}_i^s(2\gamma - \tilde{Q}_i^s - \tilde{P}_i^s - P_j^r) \\ &- \alpha_j\beta_i Q_j^s(2\gamma - Q_j^s - P_j^s - \tilde{P}_i^r) - \alpha_i\beta_j\tilde{Q}_j^s(2\gamma - \tilde{Q}_j^s - \tilde{P}_j^s - P_i^r)\end{aligned}$$

Now, by substituting the demand expressions through prices, the equation above can be rewritten as follows

$$\begin{aligned}W - \check{W} &= 2\alpha_i\beta_j(\gamma - \tilde{p}_j^s)(\gamma - p_i^s) + 2\alpha_j\beta_i(\gamma - p_j^s)(\gamma - \tilde{p}_i^s) \\ &\quad - 2\alpha_i\beta_j(\gamma - \tilde{P}_j^s)(\gamma - P_i^s) + 2\alpha_j\beta_i(\gamma - P_j^s)(\gamma - \tilde{P}_i^s) \\ &\quad = 2\alpha_i\beta_j(c_j^t - c_i^t)(c_j^k - c_i^k)\end{aligned} \tag{4.65}$$

Given that $(c_j^t - c_i^t) > 0$ and $(c_j^k - c_i^k) > 0$, it can be easily obtained that $W > \check{W}$. □

4.4.2 Bilateral Settlement Arrangements

The objective of this subsection is to analyze social welfare of the market where each provider is compensated for the costs incurred in carrying traffic.

Cost Structure and Profits

We assume that the demand and cost structures are the same as in the previous Section 4.4.1; the structure of access charges is similar as in Section 4.2.3.1. The profits of the interconnected providers can be written as follows

$$\begin{aligned}\Pi_i \quad &= \alpha_i\beta_j\left(p_i^s - c_i^o - a_k\right)q_i^s + \alpha_j\beta_i\left(\tilde{p}_i^s - c_i^o - b_k\right)\tilde{q}_i^s \\ &+\alpha_j\beta_i\left(\tilde{p}_i^r - c_i^t + b_k\right)q_j^s + \alpha_i\beta_j\left(p_i^r - c_i^t + b_k\right)\tilde{q}_j^s \end{aligned} \tag{4.66}$$

$$\begin{aligned}\Pi_j \quad &= \alpha_j\beta_i\left(p_j^s - c_j^o - a_k\right)q_j^s + \alpha_i\beta_j\left(\tilde{p}_j^s - c_j^o - b_k\right)\tilde{q}_j^s \\ &+\alpha_i\beta_j\left(\tilde{p}_j^r - c_j^t + b_k\right)q_i^s + \alpha_j\beta_i\left(p_j^r - c_j^t + b_k\right)\tilde{q}_i^s \end{aligned} \tag{4.67}$$

$$\begin{aligned}\Pi_k \quad &= a_k\left(\alpha_i\beta_j q_i^s + \alpha_j\beta_i q_j^s\right) + b_k\left(\alpha_j\beta_i\tilde{q}_i^s + \alpha_i\beta_j\tilde{q}_j^s\right) \\ &-b_k\left(\alpha_i\beta_j q_i^s + \alpha_j\beta_i q_j^s + \alpha_j\beta_i\tilde{q}_i^s + \alpha_i\beta_j\tilde{q}_j^s\right) \end{aligned} \tag{4.68}$$

It can be noticed that the profit of ISP$_k$ presents the difference between payments received from and paid to the customer providers.

Retail Prices

In order to maximize the profits, the customer providers set the retail prices for carrying traffic to the perceived marginal costs. These prices paid by the consumer for sending and receiving a unit of traffic are defined by

$$\begin{aligned} p_i^s = c_i^o + a_k \quad p_j^s = c_j^o + a_k \\ p_i^r = c_i^t - b_k \quad p_j^r = c_j^t - b_k \end{aligned} \tag{4.69}$$

and prices paid by website for subscription are given by

$$\begin{aligned} \tilde{p}_i^s = c_i^o + b_k \quad \tilde{p}_j^s = c_j^o + b_k \\ \tilde{p}_i^r = c_i^t - b_k \quad \tilde{p}_j^r = c_j^t - b_k \end{aligned} \tag{4.70}$$

Social Welfare

The following lines examine social welfare in the DTIA and classical models, both with bilateral settlements. For this purpose, we start by examining the providers' profits in the classical solution, which are given by

$$\begin{aligned}\check{\Pi}_i &= \alpha_i\beta_j\left(P_i^s - c_i^o - \check{a}_k\right)Q_i^s + \alpha_j\beta_i\left(\tilde{P}_i^s - c_i^o - \check{a}_k\right)\tilde{Q}_i^s \\ &+\alpha_j\beta_i\left(\tilde{P}_i^r - c_i^t + \check{b}\right)Q_j^s + \alpha_i\beta_j\left(P_i^r - c_i^t + \check{b}\right)\tilde{Q}_j^s \end{aligned} \tag{4.71}$$

$$\begin{aligned}\check{\Pi}_j &= \alpha_j\beta_i\left(P_j^s - c_j^o - \check{a}_k\right)Q_j^s + \alpha_i\beta_j\left(\tilde{P}_j^s - c_j^o - \check{a}_k\right)\tilde{Q}_j^s \\ &+\alpha_i\beta_j\left(\tilde{P}_j^r - c_j^t + \check{b}\right)Q_i^s + \alpha_j\beta_i\left(P_j^r - c_j^t + \check{b}\right)\tilde{Q}_i^s \end{aligned} \tag{4.72}$$

where P_i, $\tilde{P}_i$ are retail prices set to the perceived marginal costs as in DTIA; Q_i, $\tilde{Q}_i$ denote demand functions calculated analogous to the equations (4.50) and (4.51); $\check{a}_k$ and $\check{b}$ are access fees paid by ISP_k and the customer ISPs. Following the main idea of the proposed approach that a provider compensates less for costs of traffic originally initiated by customers of other networks, gives that $a_k = \check{a}_k$ and $b_k = \varepsilon a_k$. As argued $\check{b} \geq b_k$, however, to simplify studies we allow $\check{b} = b_k$. The profit of the transit provider is defined by

$$\check{\Pi}_k = \left(\check{a}_k - \check{b}\right)\left(\alpha_i\beta_j Q_i^s + \alpha_j\beta_i\tilde{Q}_i^s + \alpha_j\beta_i Q_j^s + \alpha_i\beta_j\tilde{Q}_j^s\right) \tag{4.73}$$

The social welfare functions in both models are defined by equation (4.59).

Proposition 4.20. *Social welfare in DTIA is higher than that in the classical model.*

Proof. From the expressions for the profits of the customer providers it follows that $\Pi_i = \check{\Pi}_i = \Pi_j = \check{\Pi}_j = 0$. The equations (4.50) and (4.51) result in $q_i^s = Q_i^s$ and $q_j^s = Q_j^s$. The comparison of social welfares in the DTIA and classical models is given by

$$\begin{aligned} W - \check{W} &= (a_k - b_k)(\alpha_i\beta_j(\gamma - p_i^r) + \alpha_j\beta_i(\gamma - p_j^r)) - (a_k - b_k)(\alpha_j\beta_i\tilde{Q}_i^s + \alpha_i\beta_j\tilde{Q}_j^s) \\ &= (a_k - b_k)(\alpha_i\beta_j(\tilde{P}_j^s - p_i^r) + \alpha_j\beta_i(\tilde{P}_i^s - p_j^r)) \end{aligned} \tag{4.74}$$

Given that $(\tilde{P}_j^s - p_i^r) > 0$ and $(\tilde{P}_i^s - p_j^r) > 0$, it can be obtained that $(W - \check{W}) > 0$. □

4.4.3 Discussion

The comparison results of analytical studies which investigated the impact of traffic differentiation on social welfare in the unilateral and bilateral settlement arrangements are presented in Tables 4.11-4.12 and Figures 4.4-4.5. For the calculation of specific outcomes, the following parameters are used: i) in the model with bilateral settlements, the costs are $a_k = 1.5$, $c_i^t = 0.4$, $c_j^t = 1.5$; the market shares for customers are $\alpha_i = 0.8$,

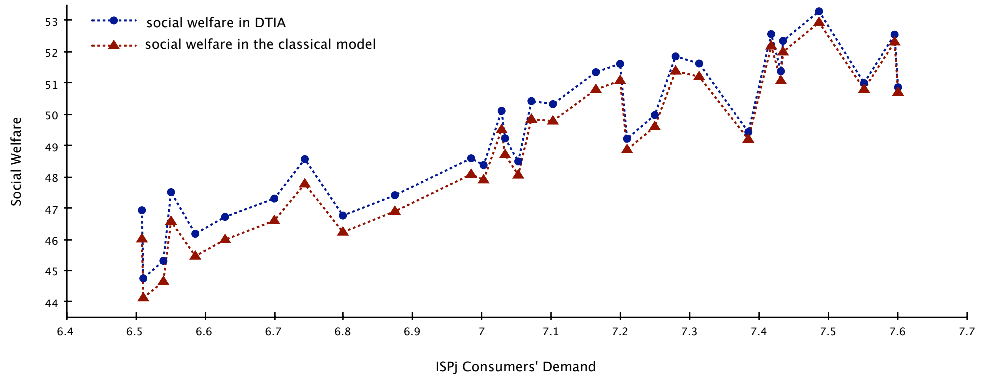


FIGURE 4.4: Social Welfare Comparison in the Unilateral Settlement Arrangements.

$\beta_i = 0.7$, and ii) in the model with unilateral settlements: $c_i^t = 0.4$, $c_j^k = 1.5$, c_i^k and c_j^t are defined randomly, where $c_i^k < c_j^k$ and $c_i^t < c_j^t$ (because ISP$_i$ is larger than ISP$_j$). According to Assumption 3.5, the number of consumers and the number of websites are set to 1. The parameters are chosen to satisfy the condition that providers operate in different cost areas. However, the specification is clearly arbitrary. It is important to note that our conclusions do not heavily depend on the chosen parameter values (see Propositions 4.19 and 4.20). The results obtained for a number of other parameter sets have not produced significant changes. Indeed, in Proposition 4.19, the expression (4.65) depends on inequalities $(c_j^t - c_i^t) > 0$ and $(c_j^k - c_i^k) > 0$ because providers operate in different cost areas where ISP$_i$ is larger than ISP$_j$. Analogously, considering Proposition 4.20, the result given by (4.74) is based on $(a_k - b_k) > 0$, $(\tilde{P}_j^s - p_i^r) > 0$ and $(\tilde{P}_i^s - p_j^r) > 0$. Hence, the provided conclusions remain the same.

Comparative results demonstrated that DTIA provided better outcomes (in terms of social welfare) than the classical model with both unilateral and bilateral settlements. More specifically, in DTIA with unilateral settlements, the increase in demand of the smaller ISP$_j$ is more than the decrease in demand of the larger ISP$_i$ (see Table 4.11 and Figure 4.4). The demand increase is achieved due to the native traffic compensation while the demand decrease is the result of the stranger traffic compensation. However, as discussed earlier, customers in different areas have different levels of affordability and willingness to pay. Hence, it is more likely that the demand decrease will be negligible (close to zero). Considering the total consumer surplus $(U_i + \tilde{U}_j)$, it can be noticed that it is higher in DTIA than in the classical solution. Finally, the results showed that DTIA stimulates the enhancement of social welfare of the system.

The following observations can be made from the comparison of bilateral settlement arrangements (see Table 4.12 and Figure 4.5). The results reported that profits of the transit provider in DTIA are less than those in the classical model. More specifically,

c_i^k	c_j^t	U_i		$\tilde{U}_j$		W		$\Delta W/\check{W}, \%$
		DTIA	**TF**	**DTIA**	**TF**	**DTIA**	**TF**	
0.781	1.953	15.663	18.046	12.586	9.667	44.415	43.879	1.221
0.735	1.874	15.686	18.261	13.052	9.936	45.186	44.645	1.213
0.211	1.956	15.738	20.184	14.714	9.305	47.653	46.691	2.062
0.424	1.299	15.743	19.741	16.439	11.976	50.683	50.219	0.925
0.769	1.045	15.746	18.489	16.083	13.113	50.263	50.037	0.452
0.472	1.051	15.729	19.660	17.230	12.978	51.998	51.677	0.622
0.679	1.620	15.727	18.601	14.216	10.862	47.130	46.649	1.031
0.305	1.811	15.741	19.921	14.911	9.922	48.060	47.250	1.714
0.428	1.099	15.730	19.813	17.211	12.768	51.946	51.586	0.698
0.555	1.080	15.738	19.318	16.783	12.895	51.312	51.003	0.605
0.630	1.129	15.744	19.003	16.298	12.734	50.555	50.251	0.605
0.525	1.036	15.733	19.452	17.075	13.058	51.772	51.474	0.578
0.820	1.075	15.746	18.279	15.765	13.013	49.765	49.545	0.444
0.593	0.986	15.734	19.204	17.008	13.283	51.693	51.438	0.496
0.424	1.869	15.728	19.432	14.239	9.776	47.005	46.246	1.641
0.686	1.386	15.743	18.680	15.080	11.758	48.579	48.194	0.799
0.545	0.954	15.727	19.405	17.325	13.393	52.185	51.931	0.489
0.750	1.235	15.746	18.497	15.416	12.364	49.164	48.863	0.616
0.357	1.974	15.724	19.619	14.094	9.335	46.708	45.844	1.884
0.519	1.371	15.746	19.336	15.788	11.741	49.663	49.206	0.929
0.316	1.190	15.728	20.220	17.299	12.358	52.031	51.582	0.870
0.294	1.345	15.738	20.230	16.770	11.730	51.152	50.605	1.082
0.455	0.940	15.716	19.768	17.739	13.416	52.813	52.542	0.515
0.229	1.722	15.746	20.268	15.548	10.220	49.079	48.272	1.670
0.417	1.342	15.744	19.745	16.294	11.803	50.441	49.951	0.980
0.645	1.237	15.746	18.902	15.816	12.317	49.774	49.430	0.695
0.207	1.403	15.736	20.542	16.885	11.457	51.287	50.665	1.228
0.289	1.589	15.746	20.115	15.833	10.773	49.597	48.907	1.413
0.366	1.480	15.746	19.875	15.958	11.241	49.855	49.267	1.193
0.345	1.514	15.746	19.939	15.904	11.094	49.753	49.135	1.257
0.455	0.975	15.720	19.758	17.603	13.276	52.593	52.305	0.551

Table 4.11: Social Welfare: Analyses of the Unilateral Settlement Arrangements.

the payments of ISP_k received from the customer ISPs are decreased which is explained by the lower access charges for stranger traffic. Obviously, the decrease in access charges leads to the fall in retail prices and consequently, to the increase in consumer surplus. Hence, the social welfare is improved since the decrease in profit of the transit provider is less than the increase in consumer surplus.

4.5 Conclusions

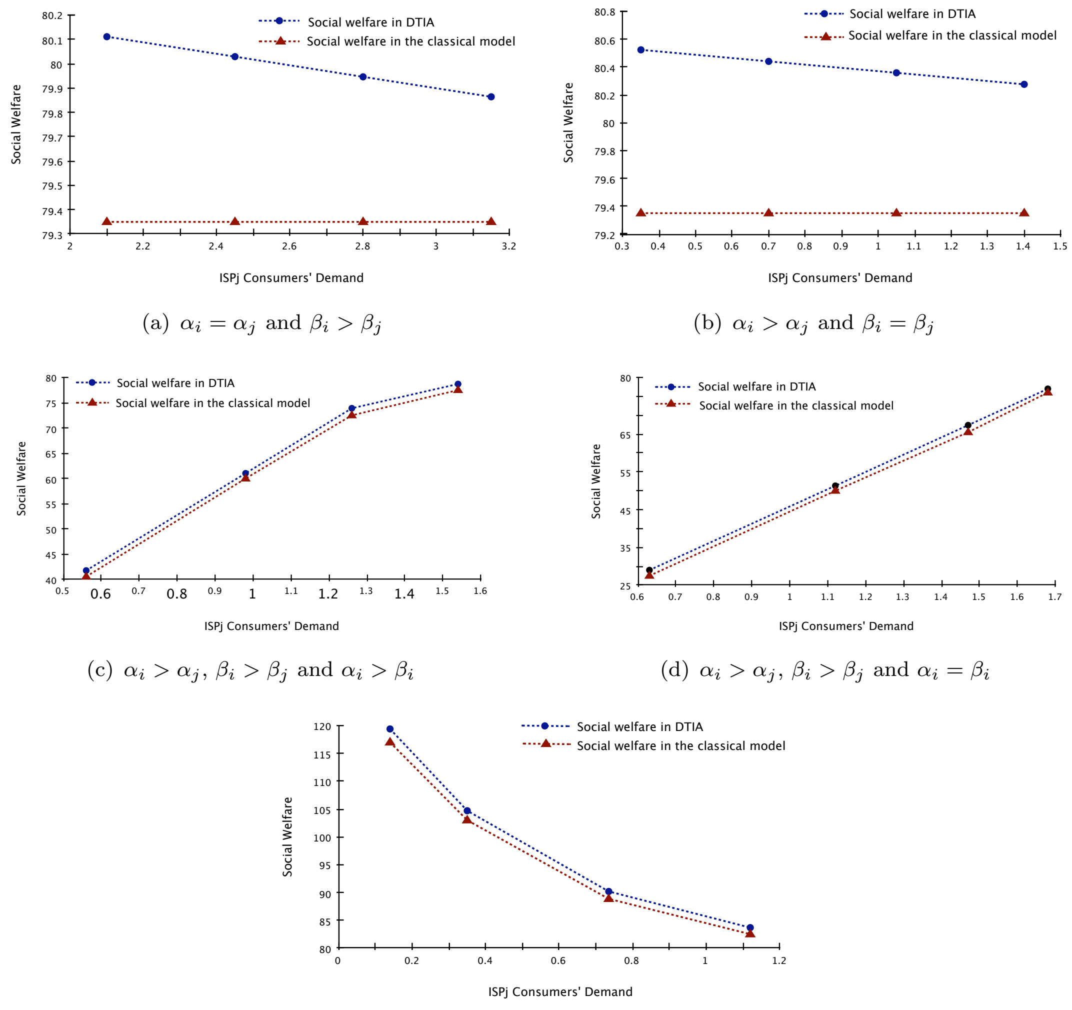
In this section we presented DTIA for intercarrier compensation considering transit arrangements. In comparison to the existing solution, the proposed model determines

Case	α_i	β_i	U		Π_k		W		$\Delta W/\check{W}, \%$
			DTIA	**TF**	**DTIA**	**TF**	**DTIA**	**TF**	
I	0.5	0.9	77.198	73.688	2.666	5.663	79.864	79.350	0.647
$\alpha_i = \alpha_j$	0.5	0.8	77.239	73.688	2.708	5.663	79.946	79.350	0.751
$\beta_i > \beta_j$	0.5	0.7	77.280	73.688	2.749	5.663	80.029	79.350	0.855
	0.5	0.6	77.321	73.688	2.790	5.663	80.111	79.350	0.959
II	0.9	0.5	77.528	73.688	2.996	5.663	80.524	79.350	1.479
$\alpha_i > \alpha_j$	0.8	0.5	77.486	73.688	2.955	5.663	80.441	79.350	1.375
$\beta_i = \beta_j$	0.7	0.5	77.445	73.688	2.914	5.663	80.359	79.350	1.271
	0.6	0.5	77.404	73.688	2.873	5.663	80.276	79.350	1.167
III	0.9	0.8	40.270	38.318	1.514	2.945	41.783	41.262	1.263
$\alpha_i > \alpha_j$	0.8	0.7	58.837	56.003	2.193	4.304	61.030	60.306	1.200
$\beta_i > \beta_j$	0.7	0.6	71.215	67.793	2.646	5.210	73.861	73.002	1.176
$\alpha_i > \beta_i$	0.6	0.55	75.836	72.214	2.795	5.549	78.631	77.763	1.116
IV	0.9	0.9	27.851	26.528	1.019	2.039	28.870	28.566	1.063
$\alpha_i > \alpha_j$	0.8	0.8	49.512	47.160	1.812	3.624	51.324	50.784	1.063
$\beta_i > \beta_j$	0.7	0.7	64.985	61.898	2.378	4.757	67.363	66.654	1.063
$\alpha_i = \beta_i$	0.6	0.6	74.268	70.740	2.718	5.436	76.986	76.176	1.063
V	0.9	0.2	114.785	109.058	4.479	8.381	119.264	117.438	1.555
$\alpha_i > \alpha_j$	0.8	0.25	100.798	95.794	3.908	7.361	104.706	103.155	1.503
$\beta_i < \beta_j$	0.7	0.35	86.790	82.530	3.315	6.342	90.106	88.872	1.388
	0.6	0.4	80.540	76.635	3.027	5.889	83.567	82.524	1.263

Table 4.12: Social Welfare: Analyses of the Bilateral Settlement Arrangements.

an original initiator of a transmission and compensates differently for traffic originally initiated by their own customers, as opposed to traffic initiated by customers of other networks. We have marked the information about the transmission initiator in the IP packet header using a two-bit field, and thus have extended the traffic management mechanism proposed earlier (in Chapter 3). The defined functionalities of the mechanism are simple and lead to low computational complexity (see Tables 4.1 and 4.2). The mechanism considers scalability issues that along with simplicity are the basic requirements for the deployment in the Internet. Further, we have addressed the issue of incentive compatibility (i.e., how to ensure that it is in the best interest of a provider to mark packets truthfully). More specifically, if a provider marks a packet untruthfully, it bears financial loss.

We have formulated economic models and analyzed their behaviors to evaluate the proposed approach from different perspectives. The studies considered unilateral and bilateral settlement arrangements. First, analytical studies were carried out to investigate the impact of the determination of a transmission initiator on interconnection payments of the customer providers (Tables 4.3-4.5). In comparison to the classical model, DTIA models with both unilateral and bilateral settlements provided significantly decreased payments of the customer providers (except the symmetric traffic volumes in case IV where payments are equal). This is mainly due to the lower access charges for stranger



(a) $\alpha_i = \alpha_j$ and $\beta_i > \beta_j$

(b) $\alpha_i > \alpha_j$ and $\beta_i = \beta_j$

(c) $\alpha_i > \alpha_j$, $\beta_i > \beta_j$ and $\alpha_i > \beta_i$

(d) $\alpha_i > \alpha_j$, $\beta_i > \beta_j$ and $\alpha_i = \beta_i$

(e) $\alpha_i > \alpha_j$ and $\beta_i < \beta_j$

FIGURE 4.5: Social Welfare Comparison in the Bilateral Settlement Arrangements.

traffic. As a result, profits of the transit provider obtained from the interconnection are lower in DTIA than in the existing scheme. Hence, it can be concluded that DTIA is beneficial for the customer providers since it outperforms the classical model in terms of payments (which are relatively small).

Furthermore, the studies were extended to explore how the determination of a transmission initiator affects different providers, operating in different cost areas and arranged interconnection with unilateral and bilateral settlements (Tables 4.6-4.10). The results obtained from analytical studies showed that DTIA was able to find better outcomes (in terms of interconnection payments) than the classical solution for both models. More specifically, the proposed model decreases the existing inequity in allocation of the interconnection costs.

From the comparison between unilateral settlement models follows that the costs of the smaller provider are decreased. This stimulates falling retail prices in the market, where the provider operates and consequently, the development of the infrastructure in terms of subscribed customers. The growth of the smaller ISP leads to a balance of the volumes of a particular traffic type, and as a result, reduces the imbalance in cost allocation between providers. Obviously, the revenue of the larger ISP obtained from the retail market will be increased. From the perspective of a transit provider, its revenues obtained from the customer providers remain the same in the DTIA and classical models. In the bilateral settlement arrangements, the net payments of both customer ISPs in the DTIA model are decreased. This leads to a decrease in the incremental revenue obtained by the transit provider. Finally, the comparison between the existing model with unilateral settlement and DTIA with bilateral settlement showed that our approach generally performed better for both smaller and larger ISPs in terms of reduced net payments. For the smaller provider, DTIA dominates in all cases over the classical model, and for the larger provider only in cases II and V. The profits of the transit provider in the bilateral settlement model are decreased since it shares the interconnection costs with other ISPs. Resuming, the provision of a model, which compensates providers while exploiting their infrastructures, is advantageous for a sustainable environment. From this point of view the proposed DTIA model is beneficial.

Finally, the results obtained from the studies which examined customers and providers indicated that DTIA in both cases (with unilateral and bilateral settlements) stimulates the economic efficiency of the market that improves overall social welfare (Tables 4.11-4.12). More specifically, consumer surplus in all cases is higher in the proposed approach than in the classical solution. Summarizing, it can be concluded that DTIA stimulates the development of the market by ensuring that each provider is compensated for utilization of its infrastructure.

Chapter 5

Conclusion and Future Work

This chapter concludes this dissertation by summarizing its contributions in Section 5.1 and by proposing directions for future work in Section 5.2.

5.1 Contributions

International Internet interconnection requires efficient costs allocation to provide sustainable conditions for all providers. This thesis provided a novel intercarrier compensation model to overcome the apparent lack of fairness in the distribution of interconnection costs. In order to achieve that we follow the principle that each provider has to be compensated for utilization of its infrastructure. The main contribution of this research is to support the development and profitability of the communications market by reducing the existing imbalance in the interconnection cost allocation. The key idea behind the proposed approach is that instead of performing intercarrier compensation based on flows of traffic, which provide a poor basis for cost allocation, compensation is performed based on the original initiator of a transmission. In the DTIA model, providers get compensated differently for traffic originally initiated by their own customers, as opposed to traffic initiated by customers of other networks. Such an approach does not admit imposition of uniform retail prices, but supports the existing diversity of the Internet pricing schemes.

A critical challenge in DTIA is determining the original initiator of a transmission in the Internet. Determination of a transmission initiator in packet-switched networks is a complicated task that deals with technical issues and incurs considerable costs. In this research, we have tackled this challenge by marking the information about the transmission initiator in the IP packet header, and have proposed a traffic differentiation mechanism that has low computational complexity. Further, we have addressed the issue of incentive compatibility (i.e., how to ensure that it is in the best interest of a provider to mark packets truthfully). More specifically, if a provider marks a packet untruthfully, it bears financial loss. In order to evaluate the impact of the traffic differentiation-based model on intercarrier compensation, we have formulated economic models and analyzed their behaviors from different perspectives (on retail and wholesale levels). The proposed approach stimulates the development of a market by ensuring that each provider is compensated for utilization of its infrastructure.

- Chapter 2 presents the background information related to this research. It discusses the fundamental differences between the telephony and Internet infrastructures in order to understand the economics of interconnection of these networks. Interconnection challenges and possible solutions, which are mainly focused on the interconnection pricing were reviewed.

Major contributions of this thesis are provided in the following Chapters:

- Chapter 3 provided Differentiated Traffic-based Interconnection Agreement (DTIA) considering private peering arrangements. Two type of traffic, namely *native* that is originally initiated by the provider's own customers and *stranger*, which is initiated by the customers of other networks were defined. Based on DTIA providers are compensated less for the costs incurred in transferring stranger traffic. To perform intercarrier compensation based on the differentiated traffic flows, a packet carries information about the traffic type, which is incorporated in the IP header using a one-bit field, referred to as Membership Label (ML); border routers support packet re-marking and counting, by performing the defined operations. Such an approach allows to avoid a detailed inspection of the packet header in order to determine the transmission initiator and its subsequent packets, and therefore leads to low computational costs. To evaluate the proposed model, economic models and their analytical studies were formulated. In particular, we investigated retail and wholesale levels of the market considering different (symmetric and asymmetric) access charges and all available market states in terms of providers' shares. More specifically, we examined the role of the transmission initiator on interconnection payments, demand, and providers' profits. At the wholesale level, the results showed that DTIA was able to achieve more fair outcomes in terms of providers' payments than the classical solution. The investigation of the retail market demonstrated that the proposed solution generates higher demand, and consequently, profits of the providers.

- Chapter 4 examines the application of the DTIA model for the transit arrangements. To achieve this, the traffic management mechanism that satisfies simplicity and scalability properties was presented. In particular, to recognize the traffic type between networks the mechanism uses a two-bit value incorporated in the IP header and supports packet re-marking and counting operations at border nodes. In order to evaluate the proposed approach a set of analytical studies were provided, considering in detail all available states of the market. At first, we considered the impact of traffic differentiation on the customer providers. Then, the benefits of different layer providers, which operate in different cost areas were examined. Finally, the studies were extended by investigating the market efficiency in terms of social welfare. The obtained results showed that DTIA with both unilateral and bilateral settlements provides better outcomes in terms of interconnection payments and social welfare than the classical model.

Summarizing the proposed model addresses the important problem of the inequality in the interconnection cost allocation. In particular, results demonstrated that our solution stimulates development of infrastructures in developing countries and on the other side, does not harm bigger or transit ISPs.

5.2 Future Work

This research brings the interconnection cost allocation issue to the forefront and makes a start in coming up with a new cost sharing indicator. Although the proposed model was analyzed from different perspectives, the studies can be extended in the technical and economical context.

- In particular, the important property of the proposed model is incentive compatibility. Although, the thesis provides the solution, it would be interesting to cover this issue in more detail.
- Another open area for further research in the economical context is the investigation of the traffic differentiation-based approach by providing mathematical analyses considering varieties of different models.

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