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Interconnection and Internet Economics: The Impact of Regulatory Policies on Peering and ISP-Content Provider Relationships

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Interconnection and Internet Economics: The Impact of Regulatory Policies on Peering and ISP-Content Provider Relationships

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Networked Systems

by

Ali Nikkhah

Dissertation Committee:
Professor Scott Jordan, Chair
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2024

DEDICATION

To my beloved wife, Zahra, whose unwavering love, support, and encouragement have been the driving force behind this achievement. Your patience and understanding during the long hours and sacrifices made this journey possible.

To my father and mother, whose unconditional love and sacrifices have paved the way for my success. Your teachings and values have instilled in me the determination and perseverance to pursue my dreams.

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This journey has been one of the most challenging yet rewarding experiences of my life. I am profoundly grateful to everyone who has been a part of it.

VITA

Ali Nikkhah

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ABSTRACT OF THE DISSERTATION

Interconnection and Internet Economics: The Impact of Regulatory Policies on Peering and ISP-Content Provider Relationships

By

Ali Nikkhah

Doctor of Philosophy in Networked Systems

University of California, Irvine, 2024

Professor Scott Jordan, Chair

Debates over paid peering and usage fees have expanded from the United States to Europe and South Korea. ISPs argue that content providers should pay fees based on the amount of downstream traffic they generate. In contrast, content providers contend that customers already pay ISPs for delivering the content they request, and therefore that peering agreements should be settlement-free. The issue has arisen in debates in the United States, Europe, and South Korea over net neutrality, universal service, and infrastructure funding. Regulatory entities are considering whether to regulate peering prices and/or impose usage fees. A key part of the debate concerns whether the market determines the socially beneficial peering price, and if not, how much of a difference there is between the socially beneficial peering price and the market-determined peering price. Our objective here is to understand the range from a cost-based peering price to a profit-maximizing peering price.

First, we determine an ISP's cost for directly peering with a content provider, by analyzing the incremental cost for transporting the content provider's traffic when it directly peers with the ISP versus when it sends its traffic through a transit provider. Next, we determine the peering price that maximizes an ISP's profit using a two-sided market model in which a profit-maximizing ISP determines broadband prices and the peering price, and in which

content providers determine their service prices based on the peering price. These prices establish a range if the peering price is unregulated, from the cost-based peering price (at the low end) to the profit-maximizing peering price (at the high end). Regulatory oversight of peering prices may be warranted when there is a substantial difference between cost-based and profit-maximizing prices.

Finally, we re-examined the arguments put forth by large ISPs and large content providers. Our results show that settlement-free peering is warranted if a content provider or transit provider provides sufficient localization of exchanged traffic. Traffic is sufficiently localized if: (1) they interconnect at a reasonable number of interconnection points, (2) the locations of these interconnection points span the country, and (3) the proportion of traffic that is exchanged at an interconnection point that is relatively close to the end user is sufficiently high.

Chapter 1

Introduction

An Internet Service Provider (ISP) enables the transmission and receipt of data to and from all or almost all Internet endpoints. To offer this Internet access service, the ISP must establish connections with other networks to exchange data. An interconnection agreement is considered a *transit service* if the transit provider agrees to accept and deliver data on behalf of the ISP, regardless of the destination. On the other hand, if each network agrees to only accept and deliver data with destinations in its customer base, the interconnection agreement is referred to as *peering*.

We focus on peering. Historically, peering was principally used by Tier 1 networks. Peering may be either paid (i.e., one interconnecting network pays the other) or settlement-free (i.e., without payment). The conventional wisdom is that two Tier 1 networks agree to settlement-free peering if and only if the two networks perceive a roughly equal exchange of value from the peering arrangement. For example, if two Tier 1 networks are both ISPs with similar numbers of customers and similar size backbones, then they may perceive a roughly equal value from the exchange of traffic with destinations in their customer cones. Large ISPs often require that peers meet certain requirements, including a specified minimum number of interconnection points, a traffic ratio less than 2:1, and symmetric routing. The conventional wisdom is that these requirements are related to the perception of roughly equal value, but the academic literature has not yet established such a relationship.

More recently, it has become common for large ISPs and large content providers or content delivery networks (CDNs) to peer. However, there have often been disagreements between them over whether the peering arrangement should be settlement-free or paid. Large ISPs advertise the same settlement-free peering requirements for content providers as for ISPs. However, large content providers do not satisfy requirements about traffic ratios, and often are more inclined to use non-symmetric routing. The academic literature has not lent much insight into when settlement-free peering between an ISP and a content provider is appropriate.

To add to the context, it is essential to understand the role of Internet Exchange Points (IXPs) in the ecosystem of network interconnection. An IXP is a physical infrastructure through which ISPs and other networks exchange Internet traffic between their networks. IXPs serve as the physical infrastructure through which networks come together to exchange traffic and interconnect directly. This interaction at IXPs underlines the importance of peering, as it is at these points that networks negotiate and manage the exchange of traffic, further emphasizing the strategic value of peering agreements in the broader Internet infrastructure.

The standard tiered interconnection model concerns the interconnection topology, interconnection services, and payment. Figure 1.1(a) illustrates the original tiered topology in which each small ISP interconnects with at least one transit provider. Transit providers interconnect with each other to provide full connectivity of the Internet. An end user obtains consumer broadband service from an ISP, in which the ISP offers to transport Internet traffic to and from all Internet endpoints. Similarly, a content provider obtains business broadband service from an ISP, in which the ISP offers to transport Internet traffic to and from all In-

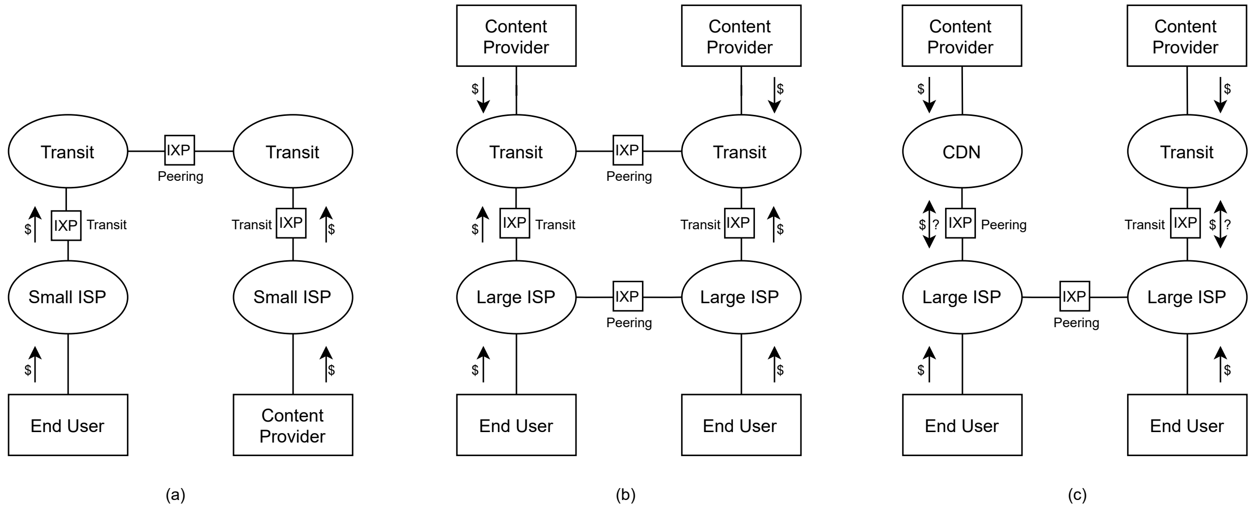

Figure 1.1: Evolution in Transit Market

ternet endpoints. An ISP obtains *transit service* from a transit provider, in which the transit provider offers to transport Internet traffic between the ISP and all Internet endpoints that are not on the ISP's network. Transit providers offer each other *peering service*s, in which each agrees to accept and deliver traffic with destinations on its own network and on the networks of its customers. In this model, end users pay their ISPs for consumer broadband service, content providers pay their ISPs for business broadband service, and ISPs pay transit providers for transit service. Transit providers do not charge each other, called *settlement-free peering*, if and only if they perceive approximately equal value to the peering service they provide to each other.

However, changes in Internet topology have led to changes in interconnection topology, interconnection services, and payment. With the progression from dial-up ISPs to broadband ISPs, large numbers of small ISPs merged to create a small number of large ISPs. These large ISPs have also built their own backbone networks to connect their service territories. Large ISPs started peering with each other to avoid having to pass this traffic through a transit provider. Content providers often interconnected with transit providers instead of small ISPs. The resulting interconnection topology is illustrated in Figure 1.1(b). As before, end users pay their ISPs for consumer broadband service. Content providers now pay transit providers for transit service. ISPs do not charge each other for peering, if and only if they perceive approximately equal value to the peering service they provide to each other. ISPs transmit traffic with destinations on other ISP's networks through peering when possible, and transmit all other traffic through transit providers. As a result, large ISPs continue to pay for transit service, but this constitutes a lower percentage of their traffic than previously.

The development and growth of CDNs led to further changes in interconnection topology, interconnection services, and payment. Third-party CDNs, wishing to deploy their servers close to consumers to improve network performance, started peering directly with large ISPs. Eventually, some large content providers built their own CDNs, and some similarly started peering directly with large ISPs. The resulting interconnection topology is illustrated in Figure 1.1(c). The majority of Internet traffic now consists of video flowing from CDNs operated by video streaming providers (e.g., Netflix) or third parties (e.g., Akamai) through direct interconnection to ISPs. As before, end users pay their ISPs for consumer broadband service. ISPs continue to transmit traffic through peering when possible, but continue to rely on transit service when needed. However, now it is unclear, when large content providers peer with large ISPs, whether large content providers should pay large ISPs, large ISPs should pay large content providers, or the peering between them should be settlement-free.

It is no longer clear who should pay whom and how much for interconnection between ISPs and content providers. Large ISPs claim that large content providers are imposing a cost on ISPs by sending large amounts of traffic to their customers. ISPs claim that it is more fair that content providers pay for this cost than consumers, because then this cost will be paid only by those consumers with high usage. In contrast, large content providers (including CDNs) claim that when they interconnect with ISPs at interconnection points (IXPs) close to consumers, they are already covering the costs of carrying traffic through the core network, and that consumers are already covering the costs of carrying traffic through the ISP's access network. These disputes between large ISPs and large content providers have recurred often during the last 10 years. When not resolved, large ISPs have often refused to increase capacity at interconnection points with large content providers and transit providers, resulting in sustained congestion which has degraded users' quality of experience because of reduced throughput, increased packet loss, increased delay, and increased jitter.

As a result, there have been an increasing number of disputes over interconnection between large ISPs, on one side, and large content providers and transit providers, on the other side. In the United States, between 2013 and 2014, a disagreement between Comcast and Netflix regarding interconnection terms persisted for an extended period. In 2014, Netflix and some transit providers brought the matter to the Federal Communications Commission (FCC) of the United States, which was drafting revised net neutrality regulations at the time. The debate shows contrasting views.

Some large content providers and some transit providers claimed that large ISPs created congestion in order to force paid peering arrangements, and that this congestion caused harm to consumers and stifled innovation. These large content providers and transit providers argue that they are covering the costs of carrying their traffic through the network, bringing it to the gateway of the Internet access service. Large content providers and transit providers argued that they should be entitled to settlement-free peering if the interconnection point is sufficiently close to consumers. The lack of willingness of large ISPs to offer settlement-free peering with large content providers, and to augment the capacity of existing interconnection points with transit providers with which they had settlement-free peering agreements, had led to the impasse. In response, large ISPs argue that content providers such as Netflix are imposing a cost on broadband Internet access service providers who must constantly upgrade infrastructure to keep up with the demand. The large ISPs explained that the network upgrades include adding capacity in the middle mile and access networks. The large ISPs asserted that if they absorb these costs, then the ISPs would recoup these costs by increasing the prices for all subscribers, which is unfair to subscribers who do not use the services, like

Netflix, that are driving the need for additional capacity. They argue that settlement-free peering is a barter arrangement in which each party should receive something of value, and if one party only sends traffic, it is not contributing anything of value. Regarding the traffic ratio, Netflix asserted that "traffic [r]atio-based charges no longer make economic sense since traffic ratios do not accurately reflect the value that networks derive from the exchange of traffic" [1]. On the other hand, Verizon asserted that "[i]f parties exchange roughly equal amounts of traffic ..., then the parties may exchange traffic on a settlement-free basis", but that "when the traffic exchange is not roughly balanced, then the net sending party typically makes a payment in order to help compensate the net receiving party for its greater relative costs to handle the other party's traffic" [2].

Both large ISPs and large content providers agree that settlement-free peering is appropriate when both sides perceive equal value to the relationship. However, whereas large content providers assert that carrying their traffic to an interconnection point close to consumers is of value, large ISPs assert that if the other party is only sending traffic, it is not contributing something of value to the broadband Internet access service provider.

The FCC addressed the debate surrounding interconnection arrangements in its 2015 Open Internet Order [3], and asserted oversight over interconnection arrangements. However, it concluded that in 2015 it was "premature to draw policy conclusions concerning new paid Internet traffic exchange arrangements between broadband Internet access service providers and [content] providers, CDNs, or backbone services." Thus, in 2015 the FCC adopted a case-by-case approach in which it would monitor interconnection arrangements, hear disputes, and ensure that ISPs are not engaging in unjust or unreasonable practices. However, in 2018, the FCC reversed its stance, as part of repealing most of the 2015 net neutrality regulations, ending this oversight [4]. However, in 2023, the FCC proposed to reinstate net neutrality rules, including oversight over interconnection agreements [5]. The FCC is expected to vote on this reinstatement in 2024, including whether to add rules or guidance specifically related to interconnection agreements. In addition, the FCC recently reported that some stakeholders are proposing that content providers pay a fee based on their download traffic to subsidize broadband Internet access service in rural areas and for low-income consumers [6]. These advocates are using similar arguments that large ISPs have used to advocate for paid peering.

Similar debates over paid peering are also active in South Korea and in Europe. In South Korea, paid peering between ISPs is now mandatory, based on the amount of traffic exchanged. As a result, these peering fees are often passed on to content providers that interconnect with ISPs in South Korea. A proposal is currently under consideration in South Korea to also require content providers to pay usage fees to ISPs, based on traffic volume [7]. The European trade association representing numerous ISPs in Europe has recently put forward a similar proposal, suggesting that content providers should pay usage fees to ISPs, based on the volume of traffic [8]. However, European regulators are concerned that such fees could be abused by ISPs and are skeptical of the argument that ISPs' costs are not adequately covered by their customers [9].

In this dissertation, we address this debate over paid peering fees. We want to determine the fair payment (if any) between an ISP and an interconnecting transit provider or content provider. We define *fair* based on the backbone transportation costs incurred by the ISP and the interconnecting network. When the fair payment is zero, we consider settlement-free peering to be a fair interconnection arrangement. Thus, we are particularly interested in the conditions under which settlement-free peering is fair. We represent value in terms of an ISP's traffic-sensitive costs. In particular, we examine settlement-free peering requirements on the minimum number of interconnection points, the locations of these interconnection points, limits on traffic ratios, and symmetric routing. We also wish to understand if it is rational to apply these settlement-free peering requirements to the interconnection between an ISP and a content provider.

We want to evaluate the effect of paid peering fees on broadband prices and consumer surplus. Our principal approach is to model the interaction between an ISP and its subscribers, and between an ISP and large content provider, as a two-sided market model. We then consider the impact of an ISP-determined paid peering fee on both consumers and content providers. Finally, we consider what level of peering fee would maximize consumer surplus. To the best of our knowledge, this is the first work to use a two-sided market model to analyze the effect of paid peering fees on broadband prices and consumer surplus.

We determine an ISP's cost for directly peering with a content provider. Such a cost-based peering price may be the minimum price an ISP will accept. We also identify the peering price that maximizes an ISP's profit using a two-sided market model. Unregulated, these prices establish a range from the cost-based peering price to the profit-maximizing peering price. Regulatory oversight of peering prices may be warranted when there is a substantial difference between cost-based and profit-maximizing prices. In particular, we want to determine the effect of content localization and the number of interconnection points on this range of peering prices.

Finally, we delve into a critical analysis of how regulatory oversight of the peering price and the unlimited usage add-on price could influence consumer surplus and societal welfare. By comparing an unregulated approach (e.g., ISP profit maximization) with regulatory approaches (e.g., maximizing consumer surplus or social welfare), we hope to gain an understanding of the potential outcomes of such regulatory interventions. Through this analysis, we seek to identify the peering price within the established range that maximizes either consumer surplus or social welfare.

In this dissertation, the terms "hot potato" routing and "cold potato" routing refer to the routing decisions made by the network provider where the originating source of the traffic is located. In hot potato routing, the network provider prefers to offload traffic to the destination network as quickly as possible, typically at the closest available interconnection point.

This strategy helps the network provider minimize its own cost by avoiding long-distance data transport. On the other hand, cold potato routing involves the network provider holding onto outgoing traffic for longer distances before handing it off to the destination network.

Furthermore, when we refer to "traffic localization," we are describing the strategy wherein the peering network directs traffic to the IXP closest to the end user. This approach ensures that the ISP often avoids transporting the traffic across its backbone network, especially when they have a peering agreement at the nearest IXP to the end user. Even in situations where they don't peer at the closest IXP, the distance the ISP needs to cover to transport the traffic over its backbone is significantly reduced.

The dissertation is organized as follows. In Section 2, we summarize the relevant research literature. Also, we summarize the settlement-free peering requirements of the ten largest ISPs in the United States. The four largest ISPs require interconnection at a minimum of 4 to 8 interconnection points from specified lists, that incoming and outgoing traffic be roughly balanced, and that the two parties use symmetric routing. The next six largest ISPs require interconnection at a specified minimum number of interconnection points, but often less than 4, and may or may not require roughly balanced traffic. We henceforth focus on the settlement-free peering requirements of the four largest ISPs.

In Section 3, we develop two cost models. The first model is an analytical model in which an ISP serves the contiguous United States with a uniformly distributed population of subscribers. The second model is a numerical model in which subscribers are distributed according to census statistics. We partition an ISP's network into access networks, middle mile networks, and a backbone network. We assume that an ISP and a transit provider or content provider mutually determine a set of points at which to interconnect, chosen from a list of the largest traffic exchange locations in the United States. In order to determine the routes over which traffic flows between networks, we construct traffic matrices, using United States census statistics to determine broadband subscriber locations. We determine the distances on an ISP's backbone network over which it carries traffic to and from a subscriber, and we calculate the average distance using the traffic matrices. We then construct a simplified model of backbone transportation costs as a function of both distance and traffic volume.

In Section 4, we analyze settlement-free peering requirements about the number and location of interconnection points between two ISPs using hot potato routing. We consider the conjecture that such requirements are related to a perception of roughly equal value. When the traffic ratio is 1:1, we show that the ISP's cost is a uni-modal function of the number of interconnection points, and that there may be little value in requiring interconnection at more than 6 Internet Exchange Points (IXPs). The ISP's cost is typically minimized by selecting interconnection points that span the country and are near population centers. Furthermore, we analyze settlement-free peering requirements about traffic ratios between two ISPs using hot potato routing. Large ISPs require that the ratio of downstream to upstream traffic not exceed a specified threshold. We consider the conjecture that this requirement is related to a perception of roughly equal value. The traffic ratio determines the trade-off between the downstream and upstream costs. We show that for traffic ratios above 2:1, the variation in the downstream cost with the number of IXPs dominates, and it is rational for the ISP not to agree to settlement-free peering. When traffic ratios are at or below 2:1, we estimate that requiring interconnection at more than 8 interconnection points is of little incremental value. Finally, we consider fair cost sharing between two ISPs. We first argue that only backbone transportation costs should be considered in determining fair cost sharing, and that middle-mile and access network transportation costs are appropriately borne by the ISP's subscribers. We briefly examine the traditional settlement-free peering arrangement between a pair of Tier-1 ISPs, and assume that such arrangements reflect fair cost sharing of backbone transportation costs. We then consider the case in which the two interconnecting ISPs have a traffic ratio other than 1. We derive a fair payment between the two ISPs based on the difference in their backbone transportation costs caused by the traffic ratio.

In Section 5, we turn to the case of an ISP interconnecting with a transit provider. Transit providers increasingly carry not only traffic indirectly passing from one ISP to another, but also content provider traffic. In this case, the ratio of downstream traffic (from the transit provider to the ISP) to upstream traffic (from the ISP to the transit provider) is likely to be higher than when two ISPs interconnect, because the content provider traffic is almost entirely downstream video traffic. The higher traffic ratio increases the ISP's backbone transportation costs. However, the transit provider may deliver a portion of the video traffic using cold potato routing, which localizes traffic on the ISP's network and reduces the ISP's backbone transportation costs. We model both the ISP's and the transit provider's backbone transportation costs, as a function of the number of interconnection points and the traffic ratio between the two, routing, and localization. Moreover, we consider fair cost sharing between an ISP and a transit provider. We first consider the case in which the transit provider uses hot potato routing for all traffic. We derive the peering fee that equalizes the ISP's and the transit provider's net costs, and show that it is similarly a function of the difference in their backbone transportation costs caused by an unequal traffic ratio. We then consider the case in which the transit provider uses cold potato routing for a proportion of the video traffic. We again derive the peering fee that equalizes the ISP's and the transit provider's net costs, and show how it depends not only on the traffic ratio, but also on the amount of video traffic and the amount of video content localization. The transit provider should pay the ISP for peering if it doesn't localize a sufficient portion of the video traffic. The fair peering fee may be positive and substantial if there is a high volume of video traffic with low localization. Finally, we consider the case in which the transit provider uses a CDN to localize traffic instead of delivering it using cold potato routing. We argue that the fair peering fee should be unchanged, and that a CDN will result in cost savings if the cost of building it is less than the cost of carrying traffic across the transit provider's backbone.

In Section 6, we analyze interconnection between a large content provider and an ISP. Large ISPs have often asserted that content providers should meet the same settlement-free peering requirements on the number of interconnection points and the traffic ratio as do ISPs in order to qualify for settlement-free peering. However, it is not clear the degree to which the settlement-free peering requirements between two ISPs should apply to interconnection between a large content provider and an ISP. We first consider a content provider that does not replicate its content and delivers traffic using hot potato routing. We show that the ISP has little incentive to engage in settlement-free peering. We next consider a content provider that replicates all of its content at peering points and delivers 100% of traffic to the ISP locally. We show that it is rational for an ISP to agree to settlement-free peering, if the content provider agrees to interconnect at a minimum of 9 IXPs. Finally, we consider a content provider that hosts a content server at peering points, but that replicates only a portion of this content on each of these servers. We show that it is rational for an ISP to agree to settlement-free peering, if the content provider agrees to interconnect at a specified minimum number of interconnection points and to deliver a specified minimum proportion of traffic locally. However, we show that a limit on the traffic ratio is not rational. Finally, we determine an ISP's cost for directly peering with a directly interconnected content provider. Such a cost-based peering price may be the minimum price an ISP will accept. To do so, we analyze the incremental cost for transporting the content provider's traffic when a content provider directly peers with the ISP versus when it sends its traffic through a transit provider. We set the cost-based peering fee such that the sum of the ISP's backbone transportation costs and the peering fee is the same when the content provider is directly or indirectly connected. We show that this cost-based peering fee depends on the localization of video traffic and the number of interconnection points. If the content provider does not localize enough video traffic, the cost-based peering fee is positive. As the content provider localizes more video traffic, the cost-based peering fee should decrease.

In Sections 7 and 8, we explore the dynamics of peering arrangements between large content providers and a profit-maximizing ISP. We present two distinct models. The first model, detailed in Section 7, offers both analytical and numerical insights into the two-sided market.

Meanwhile, the second model, discussed in Section 8, focuses solely on the numerical aspects. Additionally, the second model incorporates the consideration of an unlimited add-on fee among the variables that ISPs may charge customers. For both models, we propose a model of user subscription to broadband service tiers and to subscription video on demand (SVOD) services. We consider a monopoly ISP that offers different tiers. We aggregate all SVOD providers that directly interconnect with the ISP. Consumers differ in the utilities they place on broadband service tiers and on SVOD service, and each customer chooses the service which maximizes his/her surplus. We derive the demand of each broadband service tier and of SVOD services, the associated consumer surplus, the associated ISP profit, and aggregated SVOD providers' profit.

In Section 7, we consider a monopoly ISP that offers basic and premium tiers differentiated by bandwidth and price. To focus on the effect of peering fees, we propose a two-sided model in which a monopoly ISP maximizes its profit by choosing broadband prices as well as a peering price. An ISP earns revenue by increasing its peering price, but this will also trigger a decrease in the demand for the ISP's premium tier. An ISP also earns revenue by increasing its premium tier price, but this will also trigger a decrease in demand for SVOD services and thus in the revenue from paid peering. We derive numerical model parameters based on public data about broadband and SVOD services prices and subscription. We prove that an ISP maximizes its profit by choosing prices that satisfy a generalization of the well-known Lerner rule, which specifies how these prices are related to a matrix of elasticities and cross-elasticities of demand. We then consider the effect of paid peering on broadband prices as well as ISP profit. ISPs assert that paid peering revenue is offset by lower broadband prices, and that ISP profits remain unchanged. Content providers assert that peering prices do not result in lower broadband prices, but simply increase ISP profits. Using our model, we find that the basic tier price is almost unaffected by peering fees, but that the premium tier price is lower when an ISP chooses the paid peering price to maximize profit than when settlement-free peering is used. Also, we find that positive peering prices result in increased ISP profit and in decreased SVOD services profit. Finally, we consider the impact of paid peering on consumer surplus. ISPs assert that paid peering fees increase aggregate consumer surplus because they eliminate an inherent subsidy of consumers with high video streaming use by consumers without such use. However, content providers assert that paid peering fees decrease consumer surplus because they are passed onto consumers through higher SVOD services prices without a corresponding reduction in broadband prices. To address this question, we consider the peering price to be an independent variable set by a regulator with the goal of maximizing consumer surplus. We show that consumer surplus is a uni-modal function of the peering price, and that the peering price that maximizes consumer surplus is substantially less than the peering price that maximizes ISP profit and less than the incremental ISP cost per video streaming subscriber. We show that the peering price depends critically on this cost, and that at different costs it can be negative, zero, or positive. Then we formulate an optimization problem in which a regulator maximizes consumer surplus by choosing not only the peering price but also the broadband prices and the aggregate SVOD services price. We show that the resulting peering price is the ISP cost per SVOD services subscriber plus the desired rate of return.

In section 8, we consider a monopoly ISP that offers a basic tier and a premium tier differentiated by download speed, both with data caps, and an add-on that allows unlimited usage. We show the effect of SVOD traffic localization and the number of interconnection points on the monthly marginal costs of the ISP and SVOD providers. We then determine the peering fee that maximizes an ISP's profit. The results indicate that a profit-maximizing ISP may charge SVOD providers the highest amount their willingness to pay permits. Our research reveals that as SVOD traffic localization increases, the peering price that ISPs can demand decreases due to a reduced maximum amount that SVOD providers are willing to pay for peering. Also, our results demonstrate with a low level of localization, the peering fee charged by the profit-maximizing ISP increases as the number of interconnection points rises. However, for a high level of localization, the peering fee charged by the profit-maximizing ISP declines as the number of interconnection points increases. Finally, we compare the cost-based peering fee with the profit-maximizing peering fee. We find that the ISP's profit-maximizing peering fee typically exceeds the cost-based peering fee, and this gap may diminish with increasing traffic localization. Finally, we examine the potential implications of regulatory oversight on peering prices and unlimited usage add-on fees. We use the term "bundle price" to refer to the combined total of the peering fee and the unlimited usage add-on price. We consider a regulator that wishes to determine the bundle price that maximizes either consumer surplus or social welfare, while the ISP, with its profit-maximizing objectives, determines the pricing for the basic and premium tiers. We show that consumer surplus is a uni-modal function of the bundle price, and that the bundle price that maximizes consumer surplus is substantially less than the bundle price that maximizes ISP profit. We also show the effect of the number of interconnection points and the degree of content localization by SVOD services on the bundle prices that maximize ISP profit, social welfare, and consumer surplus.

Finally, in Section 9, we re-examine the arguments put forth by large ISPs and large content providers. Our results show that the claims of the ISPs and of the content providers are both incorrect. We reject ISP assertions that they should apply the same settlement-free peering requirements to both peering ISPs and peering content providers. We also reject ISP assertions that they should be compensated by large content providers regardless of the amount of video content localization. We also reject any assertions by transit providers or content providers that should be entitled to settlement-free peering solely because the ISP's customers have already paid the ISP to transport the traffic the content providers are sending. Instead, we argue that the settlement-free peering is warranted if a content provider or transit provider provides sufficient localization of exchanged traffic. Traffic is sufficiently localized if: (1) they interconnect at a reasonable number of interconnection points, (2) the locations of these interconnection points span the country, and (3) the proportion of traffic that is exchanged at an interconnection point that is relatively close to the end user is sufficiently high. In particular, our analysis shows that in the case of peering between an ISP and a content provider, settlement-free peering is warranted when they interconnect at a minimum of 6 interconnection points and localize at least 50% of the traffic. Therefore, we propose that the Federal Communications Commission (FCC) should require an ISP to offer settlement-free peering to content providers and transit providers that agree to reasonably localize the exchanged traffic.

The results in this dissertation were previously presented in [10–18].

Chapter 2

Review of Literature

2.1 Research Literature

A few papers examine the effects of interconnection agreements in the Internet backbone by using two-sided market models. Kim [19] is concerned with whether an ISP that is vertically integrated with a content provider may use peering fees to gain advantages over unaffiliated content providers. It proposes a two-sided market model with one monopoly ISP, one affiliated content provider, and one unaffiliated content provider. The ISP is assumed to provide direct interconnection with its affiliated content provider for free, but can choose a peering price to charge the unaffiliated content provider. The two-sided model also incorporates indirect interconnection between the unaffiliated content provider and the ISP through a transit provider. The paper finds that, when the cost of direct interconnection is low, the ISP sets the peering price at the maximum amount that the unaffiliated content provider is willing to pay, so that it earns the maximum possible revenue from direct interconnection. However, when the cost of direct interconnection is high, the ISP sets the peering price above the maximum amount that the unaffiliated content provider is willing to pay, so that the affiliated content provider has an advantage over the unaffiliated content provider. This outcome suggests that a vertically integrated ISP might exert leverage through direct interconnection in order to favor its affiliated content provider. They find consumer welfare may or may not be maximized by direct interconnection; however, this conclusion is strongly dependent on the two-sided model. The research problem addressed in [19] differs from that which we consider here. First, Kim [19] is focused on the effect of a peering price on competition between content providers, while we focus on the effect on both content providers and consumers. Second, Kim [19] adopts a game theoretic approach, while we consider both profit maximization and consumer surplus maximization.

Laffont et al. [20] are concerned with how interconnection fees between a pair of ISPs affect the allocation of network costs between consumers and content providers. It considers a two-sided model in which there is perfect competition between two ISPs, each of which can serve any customer or content provider. The model assumes that interconnection fees are symmetric between the two ISPs, but that this fee affects each ISP's market shares of consumers and of content providers. The paper finds that if an ISP has market power, then the peering price depends not only on elasticities of demand and network externalities, but also on the ISP's relative market power. Furthermore, the ISP-chosen peering price does not maximize consumer surplus. Although there are some parallels between the results of [20] and the results of our dissertation, the issues and models are quite different, since Laffont et al. [20] are concerned with interconnection fees between two competitive ISPs whereas we are concerned with interconnection fees between a monopoly ISP and content providers.

Wang et al. [21] are concerned with how interconnection fees between an ISP and content providers affect ISP profit and consumer surplus. It proposes a two-sided model in which a monopoly ISP may provide content providers the choice between paid peering and settlement-free peering and in which the ISP charges consumers an amount proportional to their monthly usage. The ISP is assumed to choose both the peering price and the consumer per-unit usage price. The paper finds that when the ISP maximizes profit, it always offers paid peering, and it may or may not also offer settlement-free peering. In contrast, when prices are set to maximize consumer surplus, the ISP always offers settlement-free peering, and it may or may not also offer paid peering. Although both [21] and our dissertation are concerned with the impact of interconnection fees on both ISP profit and consumer surplus, Wang et al. [21] are focused primarily on the ISP decision of how much capacity to allocate to paid versus settlement-free peering, whereas we are focused primarily on the ISP decision of the peering price.

Complementing the discussion on interconnection fees and their impact on network economics, Ndikumana et al. [22] introduce a novel perspective by exploring the optimization of content caching and distribution in Named Data Networking environments. Their work proposes a joint incentive mechanism for paid content caching, coupled with a price-based cache replacement policy, aimed at maximizing the profits of ISPs and content providers while improving the cache hit ratio. This approach, based on auction theory, contrasts with the focus of our dissertation on the range of peering fees based on different pricing policies and the effect of the peering fee on ISP and content provider revenue as well as consumer welfare. While we analyze how peering fees influence the strategic decisions of ISPs regarding peering arrangements, Ndikumana et al. [22] delve into the technical and economic strategies to optimize content delivery and caching, highlighting the evolving challenges and solutions in network management. Their findings offering complementary insights to our exploration of the economic and regulatory dimensions of interconnection.

In addition to these papers that use two-sided models to examine issues relating to interconnection, there is a much larger set of papers that use two-sided models to examine issues relating to net neutrality. Most of these papers are concerned with the impact of a paid prioritization prohibition on ISP profit, consumer surplus, and social welfare. We briefly discuss a few of these here. [23] uses a two-sided model in which there are multiple ISPs, each of which has a monopoly over its subscribers. Content providers connect via an ISP. It develops and analyzes a game theoretic model to study how the ability (or lack thereof) of an ISP to charge non directly connected content providers affects user prices and ISP and content provider investments. It shows that whether charging non directly connected content providers maximizes social welfare depends on the advertising revenue model and on the amount of competition between ISPs for content providers. [24] attempts to apply generic concepts from the economic literature on two-sided markets and price discrimination to the issue of paid prioritization. It claims that a monopoly ISP will set prices according to a Lerner index. It argues that the economic literature should be understood to imply that paid prioritization with price discrimination would be presumptive social-welfare enhancing. However, the validity of its conclusions is limited by the lack of a model that reflects Internet architecture, network performance, or consumer utility. [25] uses a two-sided model of a monopoly ISP to find that a paid prioritization prohibition may increase social welfare when a content provider values an additional consumer more than a consumer values an additional content provider. It also finds that the prioritization price that maximizes social welfare may be less than the associated marginal cost. [26] uses a two-sided model of two ISPs that compete based on quality and price to explore the trade-off between consumer revenue and content provider revenue. It finds that paid prioritization may increase ISP investment. It also claims that this increased ISP investment results in increased content provider revenue due to increased quality, and that consumer surplus corresponding increases. However, this claim depends on several assumptions, including a pair of competitive ISPs and the lack of a model of Internet architecture that relates access network congestion to quality. [27] uses a two-sided model of a monopoly ISP to examine how a profit-maximizing ISP may allocate capacity between two classes of service. It finds that an ISP can maximize profit by allocating all capacity to the premium class of service, while social welfare is maximized by lower premium class prices and a more balanced capacity allocation. While this literature has useful insights about the effect of prices on one side of the two-sided model on

ISP profit, consumer surplus, and social welfare, these insights relate to charging either content providers or consumers for prioritization of traffic, whereas we are focused on charging content providers for access to consumers.

Finally, there is an even larger set of papers that use two-sided models to analyze other aspects of various telecommunications markets. We briefly discuss a few of these here. [28] surveys the economic literature on two-sided models of markets involving ISPs. It reiterates the use of a Lerner index for monopoly ISPs, and then discusses the effect of competition on ISP pricing. [29] is concerned with the split of revenue between ISPs and transit providers. It considers both monopoly and competitive ISPs. It proposes the use of a Shapley value for the interconnection fee as a fair manner of splitting the revenue. [30] considers a two-sided model in which a monopoly ISP charges consumers and content providers based on the volume of traffic. It compares the prices that maximize ISP profit to those that maximize social welfare, and using a congestion model shows how these prices depend on capacity and congestion. It also shows that an ISP may be incentivized to shift from one-sided to two-sided pricing (charging content providers) as the percentage of Internet traffic that is video increases.

There are a few papers that address the issue of fair cost sharing between ISPs. Gyarmati et al. [31] consider multiple ISPs transmitting traffic over a transit provider's network. They examine various mappings from usage to cost. They show some mappings can achieve a fair and efficient allocation of costs among ISPs, while also providing incentives for network investment and capacity planning. Although they don't discuss peering fees, their results could be used to assign fair peering fees between an ISP and multiple content providers based on the traffic of content providers that passes over the ISP's backbone network. However, since they do not explicitly model peering between various parties, their estimates of cost do not explicitly consider the number of interconnection points or the localization of traffic. Wu et al. [32] propose a model for revenue sharing and rate allocation among ISPs in a two-sided market. This model, analyzed through a Stackelberg game, quantifies the loss in social profit from non-cooperative pricing strategies and introduces a profit-sharing mechanism as a solution. This approach contrasts with our study, which focuses on analyzing the alignment of market-set peering prices with socially optimal peering prices when the ISP interconnects directly with the content provider. While Wu et al. [32] explore the economic incentives for ISPs to share revenue as a means to optimize the overall network efficiency and profitability, our research delves into the regulatory implications of peering arrangements and their impact on consumer surplus and social welfare. Our dissertation emphasizes the need for regulatory oversight in cases where there's a significant discrepancy between market-set and socially optimal peering prices, exploring the effects of such discrepancies on the internet ecosystem. Alam et al. [33] explore the dynamics of traffic exchange between ISPs at IXPs as a non-cooperative game with ISPs as self-interested agents. They focus on how different pricing policies (zero, proportional, and constant pricing) impact the social cost and IXP profit. The study reveals that proportional pricing can balance the trade-off between minimizing social cost and maximizing IXP profit, offering a more robust performance against price variations compared to zero or constant pricing policies. This contrasts with our dissertation, which focuses on the broader implications of peering fees on ISP and content provider revenues and consumer welfare across different pricing policies. While Alam et al. [33] delve into the specifics of IXP operational profitability and pricing impacts on traffic exchange efficiency, our research encompasses a wider examination of peering arrangements and their economic and regulatory implications on ISPs, content providers, and consumers within the internet ecosystem.

There are some papers that focus on the economics of Internet interconnection, which involves the mechanisms and incentives for ISPs and other networks to connect with each other for the exchange of Internet traffic. Dovrolis [34] and Tan et al. [35] delve into the historical development of Internet interconnection, including the rise of content delivery networks (CDNs) and the emergence of settlement-free peering. Ma [36] and Wang et al. [37] examine the effects of different peering arrangements on Internet traffic, including the impact on network performance and congestion.

Another group of papers focus on comparing peering and transit interconnections in terms of performance and cost reduction. Castro and Gorinsky [38] propose a hybrid peering model for interconnecting transit providers and ISPs that reduces backbone transport costs. However, they focus on cost reduction for transit providers and ISPs, while we focus here on determining a fair payment for peering arrangements. Ahmed et al. [39] compare the performance of peering and transit interconnection. However, they do not consider the economic aspects of interconnection such as cost sharing, we focus on determining the fair payment between an ISP and an interconnecting transit provider or content provider for peering. Dey and Yuksel [40] compare the performance of different peering scenarios, including direct peering, public peering, and paid peering. However, they focus on the peering strategies of vertically integrated ISPs that provide both content and access services, while we focus on determining the fair payment between ISPs and content providers or transit providers for peering arrangements. Overall, the papers in this group contribute to our understanding of the trade-offs between different interconnection models and the factors that influence their performance and cost effectiveness.

There are also some papers that model the benefits and costs of peering between a CDN and an ISP. Patchala et al. [41] analyzed the economics of direct peering arrangements between a content provider and an ISP as well as peering between a CDN and an ISP. They also analyzed how sending traffic through a CDN improves the quality of service for end-users compared with sending traffic through transit providers. Lee et al. [42] analyzed the effects of CDNs on content providers and ISPs in the context of Internet traffic delivery. The authors modeled the CDN as a business-to-business platform that provides caching and other services between content providers and ISPs. While this paper does not directly address the topic of peering requirements, it provides important insights into the effects of CDN-mediated delivery on content providers and ISPs and highlights the importance of considering the impact of interconnection decisions on different parties in the network. Chang et al. [43] proposed benefit-based and cost-based frameworks for interconnection decisions by ISPs. They suggest that large ISPs choose peers based on their geographic scope and number of customers, and the traffic ratio. Agyapong and Sirbu [44] examined the relationship between ISPs and CDNs and proposed a model of how routing or interconnection choices might influence total costs and potential payment flows. However, neither paper considers the number or location of interconnection points, nor routing, and neither paper justifies traffic ratio requirements.

Another group of papers focus on CDNs and their role in Internet interconnection. Böttger et al. [45] provide an analysis of the Netflix CDN and its impact on the Internet ecosystem, including the potential for optimizing server placement, increasing the use of settlement-free peering, and exploring new interconnection models. Netflix itself describes its approach to working with network operators and content providers to improve the performance and efficiency of content delivery in [46]. These papers shed light on the role of CDNs in Internet interconnection and the implications for the Internet ecosystem.

Another group of papers focuses on paid peering, which refers to the situation where a content provider pays an ISP for the delivery of its traffic. Jitsuzumi [47] discusses a lawsuit in South Korea by Netflix against SK Broadband regarding peering fees. He presents an analysis that shows that paid peering is neutral to resource allocation when pricing is not constrained, but beneficial to ISPs and their subscribers when pricing is constrained. Wang and Ma [48] analyze the optimal pricing and contract terms for direct peering agreements between content providers and ISPs, and show that direct peering can be mutually beneficial for both parties but the pricing and contract terms should be carefully negotiated to ensure fairness and efficiency. These papers provide insights into the economic and technical factors that influence paid peering and the challenges in managing the interconnection relationships between content providers and ISPs.

Although there are many papers in the academic literature that consider various aspects of peering, there are few that analyze the common requirements of settlement-free peering policies, and fewer yet that attempt to relate these requirements to the value of the peering agreement to each interconnecting network.

PeeringDB is a database where ISPs (and other network operators) can provide information about the interconnection of their networks [49]. Lodhi et al. [50] studied PeeringDB data. They found that the volume of traffic that an ISP carries on its network is positively correlated with the number of IXPs at which it interconnects, i.e., large ISPs interconnect at many IXPs, and that ISPs with large traffic volumes and a large number of subscribers are more likely to be classified by PeeringDB as having a selective or restrictive peering inclination. However, they did not analyze the particular requirements in settlement-free peering policies (e.g., the minimum number of IXPs or the traffic ratio), instead relying on PeeringDB's more coarse classification of peering inclination (i.e., restrictive, selective, or open). We have not found any academic papers that do. The closest may be Johari and Tsitsiklis [51], who discuss the selection of IXPs in a few networks with idealized and regular topologies.

There is some work that discusses the presence of traffic ratio requirements in settlement-free peering policies. Faratin et al. [52] noted that already by 2007 large ISPs often included traffic ratio requirements in their settlement-free peering policies, and that such a requirement impacts the relative costs of the two interconnecting networks when using hot potato routing. However, they did not analyze how traffic ratios affect the costs of each party.

Dhamdhere et al. [53] and Ma [54] advocate for using a value-based framework that takes into account the mutual benefits of peering arrangements, rather than relying solely on market-based pricing mechanisms. These papers provide insights into the economic factors that influence Internet interconnection and the challenges in managing the interconnection ecosystem. However, they do not take into account the impact of traffic ratios and content localization on ISPs' backbone costs, nor do they calculate a fair peering fee between ISPs and transit or content providers. Dhamdhere et al. [53] constructed a model of ISP revenue and costs and used the model to compare peering policies that maximize profit to those with traffic ratio requirements. However, they did not analyze the effect of the traffic ratio upon costs, and thus were not concerned with relating traffic ratio requirements to the value of the peering agreement to the ISP.

Indeed, there is some work that is skeptical that traffic ratios relate to the benefits to each interconnecting party. Courcoubetis et al. [55] and Zarchy et al. [56] present various models for calculating peering prices and for evaluating the benefits of different peering strategies. Zarchy et al. [56] asserted that traffic ratio requirements do not have any relevance to the economic benefits of interconnection for each party, and that an ISP's profit may be increased by examining the benefit of each potential interconnection partner and of the potential locations of interconnection.

In addition, there is some work that points out that traffic ratio requirements are not directly relevant to the case in which an ISP interconnects with a content provider or CDN. Clark et al. [57] discussed how interconnection between a content provider and an ISP differs from the interconnection between two ISPs. They suggest a simple model of interconnection between a content provider and an ISP, and use this model to consider settlement-free peering and paid peering. In the case of paid peering, they suggest that payment may be based either on bargaining power or on traffic ratio, but point out that traffic ratio may not be an accurate representation of benefit. However, they do not analyze the effect of the number of interconnection points nor the effect of routing upon an ISP's costs.

In summary, while the existing literature provides valuable insights into the dynamics of peering agreements, our study introduces several novel contributions to the field. First, unlike previous studies that primarily focus on the economic aspects of peering between ISPs and content providers, our approach offers a comprehensive analysis that integrates both economic and technical dimensions of peering agreements. This includes a detailed examination of the impact of traffic localization and the number of interconnection points on peering fees and costs. Moreover, our study pioneers the investigation of a broad spectrum of peering fee ranges, spanning from cost-based to profit-maximizing for ISPs. Additionally, we introduce a novel framework for calculating peering fees based on factors such as the location of IXPs, the number of IXPs, traffic ratio, and the amount of localization. Finally, our dissertation proposes practical recommendations for policymakers on navigating the complex landscape of peering agreements.

2.2 Settlement-Free Interconnection Policies

We studied the settlement-free peering policies[1] of the ten largest ISPs in the United States [58–67]. Table 2.1 summarizes the most relevant requirements[2] of these policies.

The column labeled “subscribers” gives an estimate of the number of subscribers of each ISP in 2021 [68], as settlement-free peering policies differ with the number of subscribers. The column labeled “peering inclination” indicates the ISP’s predisposition towards or against peering, as noted by PeeringDB [49]. The four largest ISPs (Comcast, Charter, AT&T, and Verizon) are either selective (i.e., have moderate requirements) or restrictive (i.e., have strong requirements). The next four largest ISPs (Cox, CenturyLink[3], Altice, and Frontier) are selective. The ninth and tenth largest ISPs (Mediacom and TDS Telecom) are open (i.e., have low requirements).

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[1] Often settlement-free peering policies are called settlement-free interconnection policies.

[2] However, meeting the requirements of a settlement-free peering policy is not a guarantee that the ISP will agree to peer on a settlement-free basis; instead, it is typically viewed as the minimum requirements to start a more detailed discussion with the ISP.

[3] Throughout this dissertation, we consider CenturyLink as it was circa 2019. In 2020, it changed its name to Lumen, and it is currently attempting to sell a substantial portion of its business.

Table 2.1: Settlement-free peering requirements of the ten largest ISPs in the United States

ISP	Subscribers	Peering Inclination	Minimum Number of IXPs	Number of IXPs in ISP-Specified List	Minimum Traffic Volume	Traffic Ratio	Routing
Comcast	31,901,000	Selective	4	12	20 Gbps	Balanced	Common Policy
Charter	30,089,000	Selective	6-8	15	30 Gbps	-	Hot Potato
AT&T	15,504,000	Selective	6	12	30 Gbps	2:1	Common Policy
Verizon	7,365,000	Restrictive	8	-	12 Gbps	1.8:1	Hot Potato
Cox	5,530,000	Selective	2	15	1 Gbps	Balanced	Common Policy
CenturyLink	4,519,000	Selective	6	10	10 Gbps	1.5:1	Common Policy
Altice	4,386,200	Selective	2	-	0.1 Gbps	1.8:1	Hot Potato
Frontier	2,799,000	Selective	3	6	-	-	Hot Potato
Mediacom	1,463,000	Open	-	5	5 Gbps	-	Common Policy
TDS Telecom	526,000	Open	-	9	-	-	-

One of the most common requirements in settlement-free peering policies is a minimum number of mutually agreeable locations at which the two parties will agree to interconnect. Tier 1 ISPs typically interconnect in at least 8 of the 10 largest Internet Exchange Point (IXPs), as shown in the first ten rows of Table 2.2. In this dissertation, we use the term IXP to refer to any interconnection point where ISPs and network operators exchange traffic. While the term IXP is sometimes used to refer to neutral third-party operated exchange points, we use it more broadly to encompass all types of interconnection points. The four largest ISPs each require interconnection at a minimum of 4 to 8 IXPs (see the column labeled “minimum number of IXPs” in Table 2.1). The next four largest ISPs are varied in their characteristics. CenturyLink’s and Frontier’s backbone networks likely qualify them as Tier 1 networks, but they have significantly fewer subscribers than do the four largest ISPs. Cox’s and Altice’s backbone networks likely qualify them as Tier 2 networks. These four moderate-size ISPs require interconnection at a minimum of 2 to 6 IXPs. The ninth and tenth largest ISPs do not specify a minimum number. Amongst ISP that do specify a minimum number of mutually agreeable locations, most also require that these IXPs must be chosen from ISP-specified lists (see the column labeled “number of IXPs in ISP-specified list” in Table 2.1), and often require that the chosen IXPs be geographically diverse.

Table 2.2: The largest IXPs at which some ISPs interconnect

List of Major U.S. IXPs	**Comcast**	**Charter**	**AT&T**	**Verizon**	**Cox**	**Latitude**	**Longitude**
Ashburn	√	√	√	√	√	39.0438° N	77.4874° W
Chicago	√	√	√	√	√	41.8781° N	87.6298° W
Dallas	√	√	√	√	√	32.7767° N	96.7970° W
San Jose	√	√	√	√	√	37.3382° N	121.8863° W
Los Angeles	√	√	√	√	√	34.0522° N	118.2437° W
New York	√	√	√	√	√	40.7128° N	74.0060° W
Seattle	√	√	√	√		47.6062° N	122.3321° W
Miami	√	√	√	√		25.7617° N	80.1918° W
Atlanta	√	√	√		√	33.7490° N	84.3880° W
Denver	√	√		√		39.7392° N	104.9903° W
Boston	√				√	42.3601° N	71.0589° W
Minneapolis		√				44.9778° N	93.2650° W

Another common requirement in settlement-free peering policies is the minimum amount of traffic to be exchanged between the two networks. The three largest ISPs specify a minimum of 20 or 30 Gbps in the dominant direction (see the column labeled "minimum traffic volume" in Table 2.1). Smaller ISPs generally specify lower traffic volume thresholds, if they have such a requirement. In addition, settlement-free peering policies often require an approximate balance between incoming and outgoing traffic. Some (e.g., AT&T and Verizon) require that the ratio of incoming traffic volume to outgoing traffic volume not exceed a specified threshold. Others (e.g., Comcast) do not specify a maximum traffic ratio, but instead state the exchanged traffic should be in general balance[4].

Finally, settlement-free peering policies almost always have requirements about routing policies. Some ISPs (e.g., Charter and Verizon) require both parties to use hot potato routing[5], while other ISPs (e.g., Comcast and AT&T) only require that the two parties either both use hot potato or both use cold potato routing.

In the remainder of this dissertation, we focus on the settlement-free peering requirements

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[4] For example, Comcast requires that "[a]pplicant must maintain a traffic scale between its network and Comcast that enables a general balance of inbound versus outbound traffic. The network cost burden for carrying traffic between networks shall be similar to justify SFI." [58].

[5] The settlement-free peering policies commonly use the term "shortest-exit routing".

of the four largest ISPs.

Chapter 3

Cost Model

In this section, we develop two models of backbone transportation costs in the United States. The analysis, presented in later sections, examines the effect of routing policies, the number of IXPs at which interconnecting networks meet, and the traffic ratio between interconnecting networks on network cost. Thus, both models focus on the characteristics that we believe are most critical to this analysis, and abstract other less critical characteristics. The goal of the model is to analyze cost sharing, and in particular the dependence of network costs on traffic. We recognize that precise network costs will differ from those derived using this simplified model, but we believe that the simplified model is sufficient to illustrate the dependence of fair peering fees on the number of interconnection points, the traffic ratio, the amount of downstream content, and the amount of localization of that content.[1]

The analytical model is designed to foster closed-form analysis. It makes very simplistic assumptions. An Internet Service Provider (ISP) is assumed to serve the United States,

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[1] Outside the United States, other models may be more appropriate given differences in network topology. While the trends identified in this dissertation are likely to be similar in a qualitative way, the specific results may differ quantitatively. In addition, it should be noted that the terminology used in the dissertation (access, middle-mile, and backbone) may not be applicable in other regions. For example, in Europe, a different terminology may be used, and the relative importance of different parts of the network (such as access and middle-mile) may be different.

which is simplistically modeled as a rectangular region. Interconnection points (IXPs) are assumed to be equally spaced throughout the region. The network is partitioned into a backbone network, middle-mile networks, and access networks, each of which is similarly uniform in shape. The population is assumed to be uniformly distributed. Traffic matrices are built using these assumptions.

The numerical model is designed to reflect key characteristics of the United States. Although an ISP is still assumed to serve the United States, we now consider the actual geography of the contiguous United States. We consider the actual geographic location of the largest IXPs in the United States. Middle mile and access networks are modeled based on the U.S. counties. The density of the population is drawn from U.S. census statistics.

Although the numerical model is a more accurate representation of topologies in the United States, the analytical model also adds value to the analysis. The analytical model provides a simpler and more general understanding of the peering policies, allowing for closed-form expressions to be derived for the cost model in situations where numerical simulations are difficult due to lack of public data. Additionally, the analytical model serves as a validation tool for the numerical model by identifying potential discrepancies or errors.

To easily refer to the symbols used in this section, we provide a glossary of symbols in Table 3.1. This table includes all the symbols used in this section and their corresponding descriptions. Throughout this section, we use the subscript *ana* to denote variables pertaining to the analytical model, the subscript *num* to denote variables pertaining to the numerical model, the subscript *down* to denote downstream traffic, the subscript *up* to denote upstream traffic, the superscript *hot* to denote hot potato routing, and the superscript *cold* to denote cold potato routing.

Table 3.2 also shows a parameterization comparison between the numerical and analytical models.

Table 3.1: Symbol Glossary for Chapter 3

Symbol	Description
$A_{ana}(j,k)$	Geographical center of access network j,k
$A_{num}(j)$	Geographical center of access network j
$Access_{ana}(j,k)$	Geographical region of access network j,k
$Access_{num}(j)$	Geographical region of access network j
a	Distance from west to east of access networks
b	Distance from south to north of access networks
C	Variable portion of the ISP's traffic-sensitive cost
c^a	Cost per unit distance and volume in access network
c^b	Cost per unit distance and volume in backbone network
c^m	Cost per unit distance and volume in middle-mile network
D^a	Distance on ISP's access network
D^b	Distance on ISP's backbone network
D^m	Distance on ISP's middle-mile network
ED^a	Average distance on ISP's access network
ED^b	Average distance on ISP's backbone network
ED^m	Average distance on ISP's middle-mile network
i^p	The IXP at location IXP^p
$IXP(i)$	Location of IXP i
IXP^u	Location of the IXP closest to the end user
IXP^p	Location of the IXP at which traffic enters/exits the ISP
I	Set of locations of the IXPs
l^N	Set of N IXPs at which the ISP agrees to peer
L	Distance from west to east of the United States
N	Number of IXPs at which the ISP agrees to peer
p	Population of the contiguous United States
$P(j,k)$	Probability that an end user resides in access network (j,k)
p_j	Population of the county associated with access network j
$R(IXP(i))$	Geographical region of IXP i's access networks
s_j	Size of county j
S	Traffic source's location
U	End user's location
US	ISP's service region
V	The volume of traffic
W	Distance from south to north of the United States

Table 3.2: Parameterization Comparison between Analytical and Numerical Models

Parameters	Analytical	Numerical
ISP's service region	Rectangular US	Contiguous US
IXP Locations	Equally spaced	Actual locations
Access Network Topology	Uniform	Modeled by county
Population Distribution	Uniform	U.S. census
Distribution of sources	Uniform	County population
Distribution of end users	Uniform	County population
Calculation of distances	Euclidean	Great-circle

Our goal is to analyze the traffic-sensitive backbone transportation costs incurred by the ISP when interconnecting with another network. These costs depend on the average distance that traffic travels over the ISP's backbone, which in turn depends on routing and traffic demand patterns. To calculate the average backbone distances, we will model the ISP's service territory and construct traffic matrices representing subscriber locations. We will use these distances to derive a simplified model of the ISP's traffic-sensitive transportation costs as a function of both distance and traffic volume.

Section 3.1 introduces the topology of an ISP's U.S. network. Section 3.2 develops the traffic matrices over this network. Section 3.3 models the traffic-sensitive cost associated with carrying the traffic over the network, as a function of routing and distances.

3.1 Topology

The topology of an ISP's U.S. network consists of a model of the ISP's service territory, the location of IXPs, and a model of segments of the network.

3.1.1 Service Territory

While most ISPs do not offer residential broadband Internet access service over the entire contiguous United States, we see little in their settlement-free peering policies that are specific to their service territory other than a subset of the IXPs at which they peer that are concentrated near their service territory. Thus, in both the analytical and numerical model, we focus on a single ISP whose service territory covers the contiguous United States.

In the analytical model, the ISP's service region is simplistically modeled as a rectangular abstraction US_{ana} of the contiguous United States, measuring $L = 2800$ miles from west to east and $W = 1582$ miles from south to north [69]. We use a coordinate system (x, y) centered on this rectangle, i.e.

$$US_{ana} = \left[-\frac{L}{2}, \frac{L}{2}\right] \times \left[-\frac{W}{2}, \frac{W}{2}\right] \tag{3.1}$$

In the numerical model, the ISP's service region is modeled as the contiguous United States, denoted US_{num}, using real geographical data of its boundaries. We use a coordinate system with x and y measured in degrees of longitude and latitude, respectively.

Throughout the dissertation, we use the subscript *ana* to denote variables pertaining to the analytical model, and the subscript *num* to denote variables pertaining to the numerical model.

3.1.2 Location of IXPs

In the analytical model, we focus on the interconnection between the ISP and a single interconnecting network (e.g., another ISP or a content provider). We denote by N the number of IXPs at which the ISP and the interconnecting network agree to peer. We denote the location of IXP i ($i \in l_{ana}^N = \{1, \ldots, N\}$) by $IXP_{ana}(i)$. We simplistically assume that these N IXPs are located at the middle latitude $y = 0$ and at equally spaced longitudes x, i.e.

$$IXP_{ana}(i) = \left(-\frac{L}{2} + \frac{L(2i-1)}{2N}, 0\right) \tag{3.2}$$

We denote the set of locations of the IXPs at which the ISP interconnects with this interconnecting network by $I_{ana} = \{IXP_{ana}(i), i \in l_{ana}^N\}$.

In the numerical model, we use the actual geographic locations of the $M = 12$ largest IXPs in the United States, , located at Ashburn, Chicago, Dallas, San Jose, Los Angeles, New York, Seattle, Miami, Atlanta, Denver, Boston, and Minneapolis, listed in Table 2.2 [70–75]. The coordinates (in longitude and latitude) of these M IXPs are denoted by $IXP_{num}(i)$ i ($i = 1, ..., M$), and the set of these IXPs are denoted by I_{num}^M.

We note that the largest ISPs in the United States (Comcast, Charter, AT&T, and Verizon) each interconnect at a minimum of 9 of these 12 IXPs, although a smaller ISP (Cox) interconnects at fewer IXPs; see Table 2.2.

An ISP and an interconnecting network often agree to interconnect at a smaller number $N < M$ of IXPs. We denote the set of N IXPs at which they agree to interconnect as $l_{num}^N \subseteq \{1, \ldots, M\}$, and we denote the set of locations of these IXPs by $I_{num}^N = \{IXP_{num}(i), i \in l_{num}^N\} \subseteq I_{num}^M$.

3.1.3 Backbone Network, Middle Mile Networks, and Access Networks

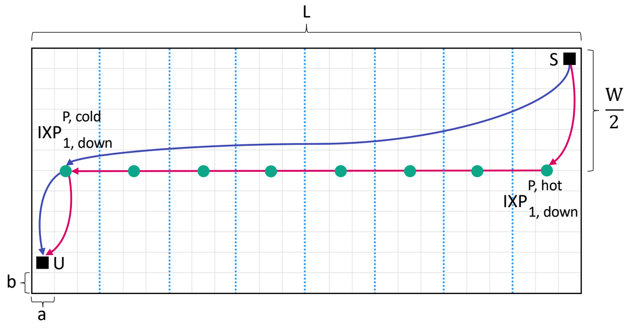
We model the ISP's network as partitioned into a single backbone network, multiple middle-mile networks, and multiple access networks. The backbone network is assumed to connect all of the IXPs at which the ISP is present. A middle-mile link is assumed to run from the geographical center of each access network to the closest IXP. While we recognize that topologies of access networks differ widely, this assumption will not affect the results in our work, since peering policies depend more critically on the location and number of interconnection points than on the topologies of access networks.

In the analytical model, we simplistically model each access network as a rectangle of size a miles from west to east and b miles from south to north. We index the access networks from west to east (j) and from south to north (k), so that a particular access network is referred to by the pair of indices (j, k), where $j = 1, \ldots, L/a$, and $k = 1, \ldots, W/b$. We denote by $Access_{ana}(j, k)$ the geographical region of access network (j, k). We denote the location of the geographical center of access network (j, k) by

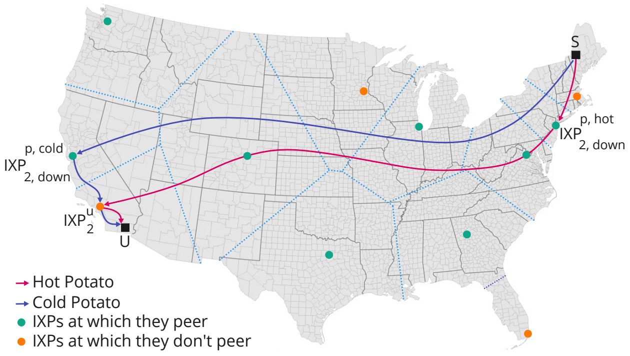
$$A_{ana}(j, k) = \left(-\frac{L}{2} + \frac{(2j-1)a}{2}, -\frac{W}{2} + \frac{(2k-1)b}{2}\right) \tag{3.3}$$

A middle-mile link is assumed to run from the geographical center of each access network (j, k) to the closest IXP, and points of presence connect the middle-mile networks with their corresponding access networks.

The backbone network is assumed to connect all of the IXPs at which the ISP is present. The IXPs thus serve both to offer interconnection between the ISP and other networks and to route traffic across the ISP's backbone network.



(a) Analytical Model



(b) Numerical Model

Figure 3.1: Topology of an ISP's network

The IXPs can be used to partition the ISP's service territory into a set of regions closest to each IXP. In the analytical model, denote by $R_{ana}(IXP_{ana}(i))$ the geographical region that consists of the union of access networks for which the closest interconnection point is IXP i, namely

$$R_{ana}(IXP_{ana}(i)) = \bigcup_{\substack{(j,k)\,|\,\|A_{ana}(j,k)-IXP_{ana}(i)\| \leq \\ \|A_{ana}(j,k)-IXP_{ana}(i')\|\ \forall i' \in I_{ana}^{N}}} Access_{ana}(j,k) \tag{3.4}$$

Figure 3.1(a) illustrates these regions for the analytical model. Since the analytical model has a regular topology, each region is simply a rectangle:

$$R_{ana}(IXP_{ana}(i)) = \left[-\frac{L}{2} + \frac{(i-1)L}{N}, -\frac{L}{2} + \frac{iL}{N}\right] \times \left[-\frac{W}{2}, \frac{W}{2}\right] \tag{3.5}$$

In the numerical model, we model each access network as spanning a single U.S. county. While we recognize that topologies of access networks differ widely, this assumption will not significantly affect the results in this dissertation, since differences in network costs between various forms of peering depend more critically on the number of interconnection points than on the topologies of access networks. We index the access networks in an arbitrary order by j. We denote by $Access_{num}(j)$ the geographical region of access network j, and we denote by $A_{num}(j)$ the location of the geographical center of access network j. These locations are assigned to be the longitudes and latitudes of the center of each county in the contiguous United States [76].

In the numerical model, consider an ISP and an interconnecting network that agree to interconnect at the N IXPs $l^N_{num} \subseteq \{1, \ldots, M\}$. For $i \in l^N_{num}$, denote by $R^N_{num}(IXP_{num}(i))$ the geographical region that consists of the union of access networks for which the closest IXP at which the ISP and the interconnecting network agree to peer is IXP i, namely

$$R^N_{num}(IXP_{num}(i)) = \bigcup_{\substack{j \,|\, \|A_{num}(j) - IXP_{num}(i)\| \leq \\ \|A_{num}(j) - IXP_{num}(i')\| \,\forall i' \in l^N_{num}}} Access_{num}(j) \tag{3.6}$$

Figure 3.1(b) roughly illustrates these regions when the ISP and an interconnecting network agree to interconnect all 12 IXPs.[2] (We will discuss the case when $N = 8$ below.)

3.2 Traffic Matrices

We now turn to modeling the traffic matrices over the ISP's network.

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[2] In the figure, the partition of the regions is only roughly illustrated. More precisely, they should follow county boundaries.

3.2.1 Distribution of Sources and End Users

The locations of end users of the ISP are represented by a probability distribution over the ISP's service territory. We decompose this distribution into (a) a distribution of the number of end users in each access network and (b) for each access network, the distribution of end users within the access network.

In the analytical model, we denote the probability that an end user resides within access network (j, k) by $P_{ana}(j, k)$. We simply assume that end users are uniformly distributed across access networks, i.e. $P_{ana}(j, k) = ab/LW$. We also simply assume that end users are uniformly distributed within each access network.

In the numerical model, we denote the probability that an end user resides within access network j by $P_{num}(j)$. We assume that end users are distributed across access networks according to the population of the county associated with the access network. We denote the population of the county associated with access network j by p_j, and we denote by $p = \sum_j p(j)$ the population of the contiguous United States. We assign these values using U.S. census data [77]. It follows that $P_{num}(j) = p_j/p$. We further assume that end users are uniformly distributed within each access network, and we denote the size of county j by s_j, which we determine using the U.S. Gazetteer [76].

We focus here on downstream traffic that originates outside the ISP's network and terminates at an end user on the ISP's network. Denote the source's location by S and the end user by U. We consider two cases. When we consider interconnection between the ISP and another ISP (which we call the ISP-ISP case), the source S is on the other ISP's network. When we consider the interconnection between the ISP and a content provider (which we call the CP-ISP case), the source S may be at an IXP at which the content provider has a server.

In the analytical model for the ISP-ISP case, we assume that the distribution of the source

S is identical to the distribution of end users, which is jointly given by $\{P_{ana}(j,k)\}$ and the uniform distribution of end users within each access network. We assume that the source S and the end user U are independent.

In the numerical model for the ISP-ISP case, we make similar assumptions, i.e. that the distributions of S and U are both jointly given by $\{P_{num}(j)\}$ and the uniform distribution of end users within each access network, and that S and U are independent.

3.2.2 Routes

In the analysis below, we distinguish between several points along traffic routes. We continue to focus on downstream traffic that originates outside the ISP's network and terminates at an end user on the ISP's network. Along the route from the source S to the end user U, denote the location of the IXP at which downstream traffic enters the ISP's network with hot potato routing by $IXP^{p,hot}_{down}$, the location of the IXP at which downstream traffic enters the ISP's network with cold potato routing by $IXP^{p,cold}_{down}$, and the location of the IXP closest to the end user by IXP^u. These points are illustrated in Figure 3.1.

For example in the numerical model, Figure 3.2 provides a rough illustration of a scenario where the ISP hosting the end user (blue ISP) and the interconnecting network (red ISP), where the source is located, agree to interconnect at $N = 8$ IXPs. Suppose S is in Maine and U is in Imperial county, California. Then, as illustrated in Figure 3.2, $IXP^{p,hot}_{down}$ might be in New York (if the two networks do not agree to peer in Boston), $IXP^{p,cold}_{down}$ might be in San Jose (if the two networks do not agree to peer in Los Angeles), and IXP^u is in Los Angeles.

The ISP offers a portion of the route from a source S to an end user U. It carries traffic on its backbone from the IXP at which traffic enters the ISP's network (IXP^p_{down}) to the IXP

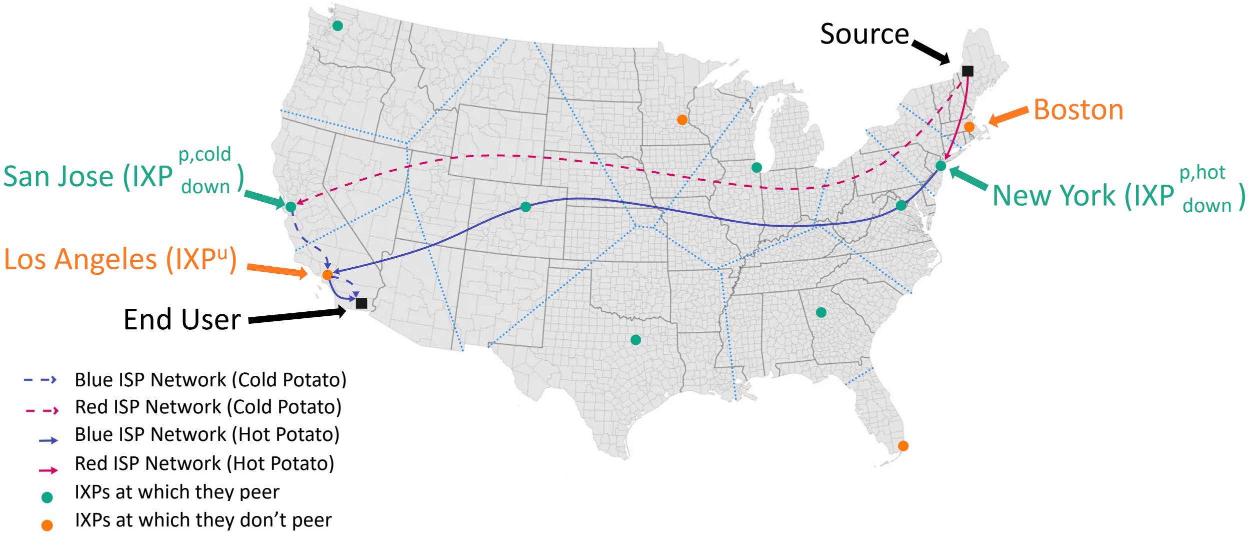

Figure 3.2: Different routing policies

closest to the end user (IXP^u), and it carries traffic on a middle-mile network and access network from the IXP closest to the end user (IXP^u) to the end user (U). The portion of the route on the ISP's network thus depends on the joint distribution of (IXP^p_{down}, IXP^u, U).

First, consider the analytical model. The end user U is uniformly distributed in US_{ana}, as discussed above. The IXP closest to the end user is a deterministic function of U, namely $IXP^u_{ana} = (g' | \, U \in R_{ana}(g'))$.

However, the IXP at which downstream traffic enters the ISP's network ($IXP^p_{ana,down}$) depends on the routing policy. If the ISP and the interconnecting network use hot potato routing, then the IXP at which downstream traffic enters the ISP's network is independent of the end user, and it is the IXP closest to the source, i.e. $IXP^{p,hot}_{ana,down} = (g | \, S \in R_{ana}(g))$. Since end users are assumed to be uniformly distributed across the contiguous U.S., $IXP^{p,hot}_{ana,down}$ is also uniformly distributed:

$$P(IXP^{p,hot}_{ana,down} = g) = \sum_{Access_{ana}(j,k) \subset R_{ana}(g)} P_{ana}(j,k) = \frac{1}{N} \tag{3.7}$$

In contrast, if the ISP and the interconnecting network use cold potato routing, then the

IXP at which downstream traffic enters the ISP's network is no longer independent of the end user, and it is the IXP closest to the end user, i.e. $IXP^{p,cold}_{ana,down} = IXP^{u}_{ana}$.

In the ISP-ISP case, there is also upstream traffic. The routes and distributions are similar, but inverted. If the ISP and the interconnecting network use hot potato routing, then the IXP at which upstream traffic enters the interconnecting network is the IXP closest to the end user, i.e. $IXP^{p,hot}_{ana,up} = IXP^{u}_{ana}$. If the ISP and the interconnecting network use cold potato routing, then the IXP at which upstream traffic enters the interconnecting network is independent of the end user and follows a distribution similar to (3.7).

We turn next to the numerical model. The access network on which U resides is distributed according to $\{P_{num}(j)\}$, and the end user U is uniformly distributed within the access network, as discussed above. The IXP closest to the end user is a deterministic function of U, namely $IXP^{u}_{num} = (g' | \, U \in R^{M}_{num}(g'))$.

However, the IXP at which downstream traffic enters the ISP's network ($IXP^{p}_{num,down}$) depends on both the routing policy and the IXPs at which they agree to interconnect. Consider an ISP and an interconnecting network that agree to interconnect at the N IXPs in I^{N}_{num}. If the ISP and the interconnecting network use hot potato routing, then the IXP at which downstream traffic enters the ISP's network ($IXP^{p,hot}_{num,down}$) is independent of the end user, and it is the IXP closest to the source among the IXPs at which they agree to peer, i.e. $IXP^{p,hot}_{num,down} = (g | \, S \in R^{N}_{num}(g))$. Since end users are assumed to be distributed according to U.S. county population statistics, $IXP^{p,hot}_{num,down}$ is distributed as:

$$\begin{aligned} P(IXP^{p,hot}_{num,down} = g) &= \sum_{Access_{num}(j) \subset R^{N}_{num}(g)} P_{num}(j) \\ &= \frac{1}{p} \sum_{Access_{num}(j) \subset R^{N}_{num}(g)} p(j) \end{aligned} \tag{3.8}$$

In contrast, if the ISP and the interconnecting network use cold potato routing, then the IXP at which downstream traffic enters the ISP's network ($IXP^{p,cold}_{num,down}$) is no longer independent of the end user, and it is the IXP closest to the end user at which they agree to peer, i.e. $IXP^{p,cold}_{num,down} = (g|\, U \in R^{N}_{num}(g))$.

For upstream traffic in the numerical model, the routes and distributions are again similar, but inverted. If the ISP and the interconnecting network use hot potato routing, then the IXP at which upstream traffic enters the interconnecting network is the IXP closest to the end user at which they agree to peer, i.e. $IXP^{p,hot}_{num,up} = (g|\, U \in R^{N}_{num}(g))$. If the ISP and the interconnecting network use cold potato routing, then the IXP at which upstream traffic enters the interconnecting network is independent of the end user and follows a distribution similar to (3.8).

3.3 Traffic-sensitive Costs

Although we know that an ISP's traffic-sensitive cost is a complicated function of the topology of the network, to make the analysis tractable, we abstract the network geographically into three non-overlapping sections: backbone, middle-mile, and access. We define the backbone network as the set of links between IXPs. We define the middle-mile networks as the set of links between the geographical center of each access network and the closest IXP. We define the access networks as the set of links that connect the middle-mile networks to end users.

In this section, we first determine the distances on each portion of its network that an ISP carries traffic from a source to an end user. We next calculate the average distance using the traffic matrices above. Finally, we model the traffic-sensitive cost associated with carrying the traffic over these average distances.

3.3.1 Distances

We first determine distances in the analytical model. We continue to focus on downstream traffic that originates outside the ISP's network and terminates at an end user on the ISP's network. The distances on each section on the ISP's network depend on the joint distribution of $(IXP^p_{ana,down}, IXP^u_{ana}, U)$. All distances in the analytical model are Euclidean distances between the corresponding points on a plane.

The distance on the ISP's backbone network is a function of the location of the IXP at which downstream traffic enters the ISP's network ($IXP^p_{ana,down}$) and the location of the IXP closest to the end user (IXP^u_{ana}). We denote the distance on the ISP's backbone network between these two IXPs by $D^b_{ana}(IXP^p_{ana,down}, IXP^u_{ana}) = \|IXP^p_{ana,down} - IXP^u_{ana}\|$. Denote by i^p the IXP at location $IXP^p_{ana,down}$, i.e. $i^p = i|(IXP^p_{ana,down} = IXP_{ana}(i))$, and denote by i^u the IXP at location IXP^u_{ana}, i.e. $i^u = i|(IXP^u_{ana} = IXP_{ana}(i))$. The distance between two IXPs can be determined by their locations given in (3.2):

$$D^b_{ana}(IXP^p_{ana,down}, IXP^u_{ana}) = \frac{L}{N}|i^p - i^u| \tag{3.9}$$

The distance on the ISP's middle-mile network is a function of the location of the IXP closest to the end user (IXP^u_{ana}) and the location of the access network on which the end user (U) resides. We denote the distance on the ISP's middle-mile network between these two locations by $D^m_{ana}(IXP^u_{ana}, U) = \|IXP^u_{ana} - A_{ana}(j,k)\|$, where $U \in R_{ana}(IXP^u_{ana})$ and $(j,k)\,|\,(U \in Access_{ana}(j,k))$. The distance can be determined by the locations of the IXP and the access network, given in (3.2)-(3.3):

$$\begin{aligned} &D^m_{ana}(IXP^u_{ana}, U) = \\ &\sqrt{\left(\frac{L(2i^u-1)}{2N} - \frac{(2j-1)a}{2}\right)^2 + \left(-\frac{W}{2} + \frac{(2k-1)b}{2}\right)^2} \end{aligned} \tag{3.10}$$

where $U \in R_{ana}(IXP^u_{ana})$ and $(j,k) \,|\, (U \in Access_{ana}(j,k))$.

The distance on the ISP's access network is a function of the location of the end user. We denote the distance on the ISP's access network by $D^a_{ana}(U) = \|A_{ana}(j,k) - U\|$, where $(j,k) \,|\, (U \in Access_{ana}(j,k))$. The distance can be determined by the location of end user within the access network.

The distances in the numerical model can be similarly represented as $D^b_{num}(IXP^p_{num,down}, IXP^u_{num}) = \|IXP^p_{num,down} - IXP^u_{num}\|$, $D^m_{num}(IXP^u_{num}, U) = \|IXP^u_{num} - A_{num}(j)\|$ (where $U \in R^M_{num}(IXP^u_{num})$), and $D^a_{num}(U) = \|A_{num}(j) - U\|$, where $j \,|\, (U \in Access_{num}(j))$. All distances in the numerical model are great-circle distances between the corresponding points on a sphere, and are calculated using the Haversine formula. However, there are no closed form formulae for these distances.

3.3.2 Average Distances

An ISP's traffic-sensitive cost depends on the average distance of traffic on each segment of its network. As discussed above, the distances on each section of the ISP's network depend on the joint distribution of (IXP^p, IXP^u, U). This joint distribution was given in Section 3.2 for both models, separately for hot potato routing and for cold potato routing.

We first determine average distances in the analytical model. We continue to focus on downstream traffic that originates outside the ISP's network and terminates at an end user on the ISP's network. The distance on the ISP's backbone network is a function of $(IXP^p_{ana,down}, IXP^u_{ana})$. When hot potato routing is used, the IXP at which downstream traffic enters the ISP's network ($IXP^{p,hot}_{ana,down}$) is independent of the end user and thus independent of the IXP closest to the end user (IXP^u_{ana}). Thus, the average distance on the

ISP's backbone network is:

$$ED^{b,hot}_{ana,down} = \sum_{g \in I_{ana}} \sum_{g' \in I_{ana}} D^{b}_{ana}(g, g') P(IXP^{p,hot}_{ana,down} = g) P(IXP^{u}_{ana} = g') \tag{3.11}$$

The distance $D^{b}_{ana}(g, g')$ is given in closed form in (3.9). The probability distribution of $IXP^{p,hot}_{ana,down}$ is given in (3.7), and the probability distribution of IXP^{u}_{ana} is similarly uniformly distributed. We can use these results to give a closed-form expression:

Theorem 3.1. *In the analytical model, the average distance on the ISP's backbone network is:*

$$ED^{b,hot}_{ana,down} = \frac{L(N-1)(N+1)}{3N^2} \tag{3.12}$$

The proof can be found in the Appendix A.

When cold potato routing is used, the IXP at which downstream traffic enters the ISP's network ($IXP^{p,cold}_{ana,down}$) is the IXP closest to the end user, i.e. $IXP^{p,cold}_{ana,down} = IXP^{u}_{ana}$. Thus, the ISP does not carry traffic across its backbone, i.e.

$$ED^{b,cold}_{ana,down} = 0 \tag{3.13}$$

The distance on the ISP's middle-mile network is a function of (IXP^{u}_{ana}, U). It is independent of the routing policy, and the average distance is:

$$ED^{m}_{ana} = \sum_{g' \in I_{ana}} \sum_{A_{ana}(j,k) \subset R_{ana}(g')} D^{m}_{ana}(g', A_{ana}(j,k)) P_{ana}(j,k) \tag{3.14}$$

The distance $D^{m}_{ana}(g', A_{ana}(j,k))$ is given in closed form in (3.10). Also, $P_{ana}(j,k) = ab/LW$.

We can use these results to give a closed form expression:

Theorem 3.2. *In the analytical model, the average distance on the ISP's middle-mile network is:*

$$ED^{m}_{ana} = \frac{abN}{LW}\sum_{k=1}^{\frac{W}{b}}\sum_{j=1}^{\frac{L}{aN}}\sqrt{\left(\frac{(2j-1)a-\frac{L}{N}}{2}\right)^2+\left(\frac{(2k-1)b-W}{2}\right)^2} \tag{3.15}$$

The proof can be found in the Appendix B.

The distance on the ISP's access network is a function of U. It is also independent of the routing policy. Since end users are uniformly distributed between access networks and also within each access network, the average distance is:

$$ED^{a}_{ana} = \frac{1}{ab}\int_{-\frac{a}{2}}^{\frac{a}{2}}\int_{-\frac{b}{2}}^{\frac{b}{2}}\sqrt{x^2+y^2}\,dy\,dx \tag{3.16}$$

It can be shown that:

Theorem 3.3. *In the analytical model, the average distance on the ISP's access network is:*

$$ED^{a}_{ana} = \frac{1}{12ab}\left[a^3\sinh^{-1}(\frac{b}{a})+b^3\sinh^{-1}(\frac{a}{b})+2ab\sqrt{a^2+b^2}\right] \tag{3.17}$$

The proof can be found in the Appendix C.

We next determine average distances in the numerical model. We continue to focus on downstream traffic that originates outside the ISP's network and terminates at an end user on the ISP's network. The distance on the ISP's backbone network is a function of $(IXP^{p}_{num,down}, IXP^{u}_{num})$.

As in the analytical model, when hot potato routing is used, the IXP at which downstream traffic enters the ISP's network ($IXP^{p,hot}_{num,down}$) is independent of the end user and thus independent of the IXP closest to the end user (IXP^{u}_{num}). However, whereas in the analytical model the IXP at which downstream traffic enters the ISP's network depends only on the routing policy, in the numerical model it also depends on the IXPs at which they agree to interconnect. Consider an ISP and an interconnecting network that agree to interconnect at the N IXPs in I^{N}_{num}. The average distance of the downstream traffic on the ISP's backbone network, which flows from the source S to the user U, is:

$$\begin{split} &ED^{b,hot}_{num,down} = \\ &\sum_{g \in I^{N}_{num}} \sum_{g' \in I^{M}_{num}} D^{b}_{num}(g,g') P(IXP^{p,hot}_{num,down} = g) P(IXP^{u}_{num} = g') \end{split} \tag{3.18}$$

The probability distribution of $IXP^{p,hot}_{num,down}$ was given in (3.8). The probability distribution of IXP^{u}_{num} can be similarly represented as:

$$\begin{split} P(IXP^{u}_{num} = g') &= \sum_{Access_{num}(j) \subset R^{M}_{num}(g')} P_{num}(j) \\ &= \frac{1}{p} \sum_{Access_{num}(j) \subset R^{M}_{num}(g')} p(j) \end{split} \tag{3.19}$$

For downstream traffic using cold potato routing, the IXP at which downstream traffic enters the ISP's network ($IXP^{p,cold}_{num,down}$) is the IXP closest to the end user at which they agree to peer. In addition, $IXP^{p,cold}_{num,down}$ is no longer independent of IXP^{u}_{num}. Since they might not agree to peer at all IXPs, the ISP might still carry traffic across a portion of its backbone, namely from $IXP^{p,cold}_{num,down}$ to IXP^{u}_{num}, and the average such distance, which flows from the source S to the user U, is:

$$\begin{aligned} ED^{b,cold}_{num,down} = \sum_{g' \in I^M_{num}} \sum_{g \in I^N_{num}} \\ D^b_{num}(g, g') P(IXP^{\text{p,cold}}_{num,down} = g, IXP^u_{num} = g') \end{aligned} \tag{3.20}$$

Now, since for each g', there exists a unique g which minimizes the backbone distance $D^b_{num}(g, g')$, and this g is chosen based on the condition $g' \in R^N_{num}(g)$, we can simplify Equation (3.20). In this context, $R^N_{num}(g)$ denotes the set of IXPs at which the ISP agrees to peer, given that the traffic has entered the network at IXP g.

With this assumption, for each g', we select the g that minimizes $D^b_{num}(g, g')$. Consequently, the inner sum in Equation (3.20) collapses to a single term for each g', and the equation simplifies to:

$$ED^{b,cold}_{num,down} = \sum_{g' \in I^M_{num}} D^b_{num}(g \mid g' \in R^N_{num}(g), g') P(IXP^u_{num} = g') \tag{3.21}$$

The distance on the ISP's middle-mile network is a function of (IXP^u_{num}, U). It is independent of the routing policy, and the average distance is:

$$ED^m_{num} = \sum_{g' \in I^M_{num}} \sum_{A_{num}(j) \subset R^M_{num}(g')} D^m_{num}(g', A_{num}(j)) P_{num}(j) \tag{3.22}$$

The distance on the ISP's access network is a function of U. It is also independent of the routing policy. Since end users are uniformly distributed within each access network, but not between access networks, the average distance is:

$$ED^a_{num} = \sum_j \frac{p_j}{ps_j} \int_{U \in Access_{num}(j)} D^a_{num}(U) \tag{3.23}$$

3.3.3 Cost

The ISP incurs a traffic-sensitive cost for carrying traffic over the average distances calculated in the previous subsection. We only consider here traffic-sensitive costs, because non-traffic-sensitive costs do not vary with routing policies, the number of interconnection points, or traffic ratio.[3]

Traffic-sensitive costs are a function of both distance and traffic volume. We assume here that traffic-sensitive costs are linearly proportional to the average distance over which the traffic is carried on each portion of the ISP's network, see e.g., [78]. We also assume that traffic-sensitive costs are linearly proportional to the average volume of traffic that an ISP carries on each portion of its network. Although the cost might be an increasing concave function of traffic volume (or a piecewise constant function), the linear model will suffice for our analysis.

We model the cost per unit distance and per unit volume differently on the backbone network, the middle-mile networks, and the access networks. Denote the cost per unit distance and per unit volume in the backbone network by c^b, the cost per unit distance and per unit volume in the middle-mile networks by c^m, and the cost per unit distance and per unit volume in the access network by c^a. Denote the volume of traffic by V. The ISP's traffic-sensitive cost is thus $V\left(c^b ED^b + c^m ED^m + c^a ED^a\right)$.

In the analysis below, we fix the source-destination traffic matrix, and we consider the effect of changes in the number of IXPs at which peering occurs, routing policies, and the traffic ratio.

In the analytical model, given a fixed source-destination traffic matrix, the average distance across the ISP's access networks in (3.17) is constant. Thus, the ISP's traffic-sensitive access

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[3] There is a small cost for each interconnection points; however, this cost is relatively small compared to transportation costs.

network cost is similarly constant. The variable portion of the ISP's traffic-sensitive cost is thus:

$$C_{ana} = c^b \left(ED^b_{ana} + \frac{c^m}{c^b} ED^m_{ana} \right) V \tag{3.24}$$

Below we consider the effect on the variable traffic-sensitive cost (C_{ana}) of changes in the number of IXPs at which peering occurs, routing policies, and the traffic ratio, for constant c^b and different ratios of c^m/c^b. (In the remainder of the dissertation, we use the term *cost* to refer to the variable traffic-sensitive cost.) We will find that changes in the number of IXPs, routing policies, and the traffic ratio all affect ED^b_{ana} and/or ED^m_{ana}.

In the numerical model, given a fixed source-destination traffic matrix, the average distance across the ISP's access networks in (3.23) is similarly constant. In addition, the average distance across the ISP's middle-mile networks in (3.22) is constant, once we fix $M = 12$, since the IXPs at which the parties agree to peer do not affect the middle-mile. The variable portion of the ISP's traffic-sensitive cost is thus only:

$$C_{num} = c^b ED^b_{num} V \tag{3.25}$$

Below we consider the effect on the variable traffic-sensitive cost (C_{num}) of changes in the number of IXPs at which peering occurs, routing policies, and the traffic ratio, for constant c^b. We will find that changes in the number of IXPs at which peering occurs, routing policies, and the traffic ratio all affect ED^b_{num}.

Chapter 4

Peering Between Two ISPs

In this section, we analyze peering between two ISPs. With both the analytical and numerical models in place, we now turn to analyzing the effect on an ISP's variable traffic-sensitive costs of the number of IXPs at which peering occurs, routing policies, and the traffic ratio. We are in particular interested in explaining the settlement-free peering policies of large ISPs, why large ISPs require settlement-free peers to meet at a minimum of 4-8 IXPs, and also why these IXPs are geographically distributed across the country.

We propose that customers bear middle-mile and access costs, and that peering fees result in fair cost sharing between the two ISPs of backbone costs. We calculate the peering fee necessary for equitable cost-sharing and investigate how traffic ratios affect the costs and payments between the two parties.

We consider peering between two ISPs of comparable size and traffic, i.e., the same number of customers, similar backbone sizes, and the same amount of upload and download traffic. The results indicate that as long as there is symmetry in the arrangement, these ISPs would likely reach a settlement-free peering agreement.

Next, we consider peering between two ISPs that carry unequal traffic. In this case, there may be payment between the two networks. The payment will depend on the traffic ratio, as we will analyze in this section.

We assume that the ISPs share a similar network topology. This means that the mathematical models and equations presented are applicable from the perspective of any of the involved ISPs.

To easily refer to the symbols used in this section, we provide a glossary of symbols in Table 4.1. This table includes all the symbols used in this section and their corresponding descriptions. Throughout this section, we use the subscript *ana* to denote variables pertaining to the analytical model, the subscript *num* to denote variables pertaining to the numerical model, the subscript *down* to denote downstream traffic, the subscript *up* to denote upstream traffic, the superscript *hot* to denote hot potato routing, and the superscript *cold* to denote cold potato routing.

4.1 The Effect of Number of Interconnection Points

In this section, we examine the effect of the number of IXPs at which two ISPs agree to peer, and the list of IXPs at which they peer. As shown in Table 2.1, large ISPs require other ISPs who wish to have settlement-free peering to interconnect at a minimum specified number of IXPs. For Comcast, Charter, AT&T, and Verizon, this minimum is between 4 and 8. In addition, large ISPs often specify a list of eligible IXPs that this minimum must be chosen from. The academic literature provides little insight into why large ISPs require interconnection at a minimum specified number of IXPs, nor why they require that they be selected from a list of eligible IXPs.

In order to better understand these requirements of settlement-free peering policies, we

Table 4.1: Symbol Glossary for Chapter 4

Symbol	Description
C	Traffic-sensitive cost
C^{ISP}	ISP traffic-sensitive backbone cost
c^b	Cost per unit distance and volume in backbone network
c^m	Cost per unit distance and volume in middle-mile network
ED^b	Average distance on backbone network
ED^m	Average distance on middle-mile network
$IXP(i)$	Location of IXP i
IXP^u	Location of the IXP closest to the end user
IXP^p	Location of the IXP at which traffic enters/exits the ISP
I	Set of locations of the IXPs
l^N	Set of N IXPs at which the ISP agrees to peer
L	Distance from west to east of the United States
M	Number of major IXPs
N	Number of IXPs at which the ISP agrees to peer
P^{ISP^2,ISP^1}	Peering fee that ISP^2 pays ISP^1
r	Ratio of downstream to upstream traffic
$R(IXP(i))$	Geographical region of IXP i's access networks
S	Traffic source's location
U	End user's location
V	Volume of traffic

initially focus only on downstream traffic that originates outside the ISP's network and terminates at an end user on the ISP's network. We first assume that both ISPs use hot potato routing.

Using the analytical model, the cost of downstream traffic is:

$$C^{hot}_{ana,down} = c^b V_{down} \left(ED^{b,hot}_{ana,down} + \frac{c^m}{c^b} ED^m_1 \right) \tag{4.1}$$

Substituting the expressions we previously found for $ED^{b,hot}_{ana,down}$ in (3.12) and for ED^m_1 in (3.15), we obtain:

$$\begin{aligned} C^{hot}_{ana,down} = c^b V_{down} \Bigg(& \frac{L(N-1)(N+1)}{3N^2} + \frac{c^m}{c^b} \frac{abN}{LW} \\ & \sum_{m=1}^{\frac{W}{b}} \sum_{n=1}^{\frac{L}{aN}} \sqrt{\left(\frac{(2n-1)a - L/N}{2} \right)^2 + \left(\frac{(2m-1)b - W}{2} \right)^2} \Bigg) \end{aligned} \tag{4.2}$$

Figure 4.1(a) shows the effect of number of interconnection points (N) on the cost of downstream traffic ($C^{hot}_{ana,down}$), when $c^m/c^b = 1.5$. (The costs in the figure are normalized by the cost per unit distance and per unit volume, and by the combined downstream and upstream traffic volume.) The number of interconnection points affects both the backbone cost and the middle mile cost.

The average distance the ISP carries traffic across its backbone ($ED^{b,hot}_{ana,down}$) is proportional to $1 - \frac{1}{N^2}$. Thus, the backbone cost is increasing and concave with the number of interconnection points. A larger number of interconnection points results in a larger distance between the IXP closest to the west coast and the IXP closest to the east coast. As a result, the backbone expands and the ISP carries traffic across a longer distance on this larger backbone.

The average distance the ISP carries traffic across its middle mile networks (ED^m_1) is a complicated function of N. However, as we see in Figure 4.1(a), the middle mile cost is decreasing and convex with the number of interconnection points. A larger number of interconnection points results in more closely spaced IXPs that are closer to the access networks. As a result, the middle mile networks shrink as the backbone expands.

In the analytical model, therefore, increasing the number of interconnection points increases backbone cost and decreases middle mile cost. The variation of the sum of these two costs with the number of interconnection points depends on the ratio of the per unit costs of the backbone and the middle mile. For relatively small values of c^m/c^b (e.g. 1.5), the cost of downstream traffic is a uni-modal function of N. For relatively large values of c^m/c^b, the cost of downstream traffic is decreasing with N, since the middle mile costs dominate; an example is shown in Figure 4.1(b) when $c^m/c^b = 3$.[1]

However, when two ISPs peer, there is also upstream traffic. Using the analytical model, the cost of upstream traffic using hot potato routing is:

$$C^{hot}_{ana,up} = c^b V_{up} \left(ED^{b,hot}_{ana,up} + \frac{c^m}{c^b} ED^m_1 \right) \tag{4.3}$$

As we discussed in Section 3.2.2, the route that upstream traffic takes when using hot potato routing is the same route (but in the opposite direction) that downstream traffic takes when using cold potato routing. The average distance the ISP carries traffic across its middle mile networks (ED^m_1) is the average distance between the center of the access network and the nearest IXP, which is the same for downstream and upstream traffic. In addition, the average distance the ISP carries upstream traffic across the backbone when using hot potato routing is the same as the average distance the ISP carries downstream traffic across the

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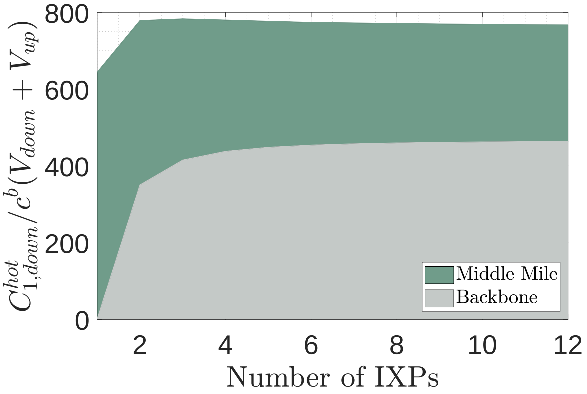
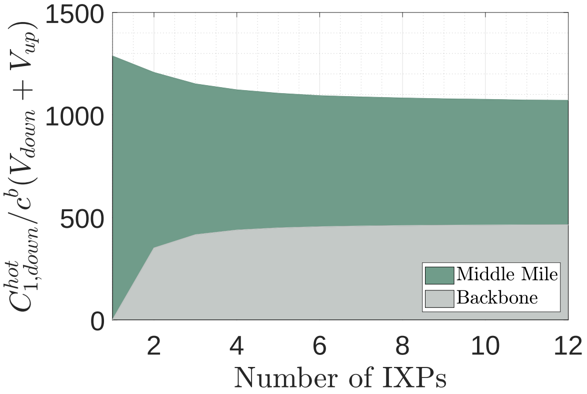
[1] We use values of 1.5 and 3 for the parameter c^m/c^b in our analytical model to analyze the effect of interconnection points on downstream traffic cost. However, due to the lack of publicly available data on network cost structures, determining a representative value can be challenging.



(a) $c^m/c^b = 1.5$



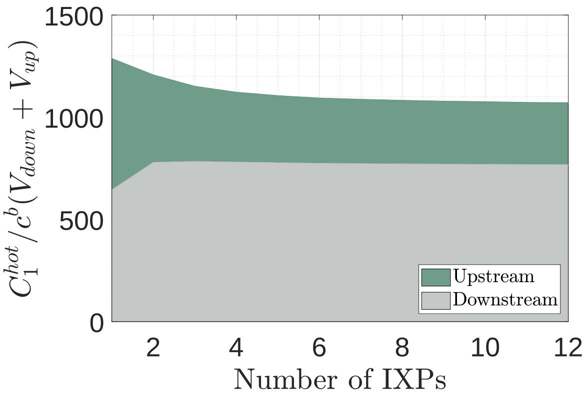
(b) $c^m/c^b = 3$

Figure 4.1: Downstream costs (analytical model)

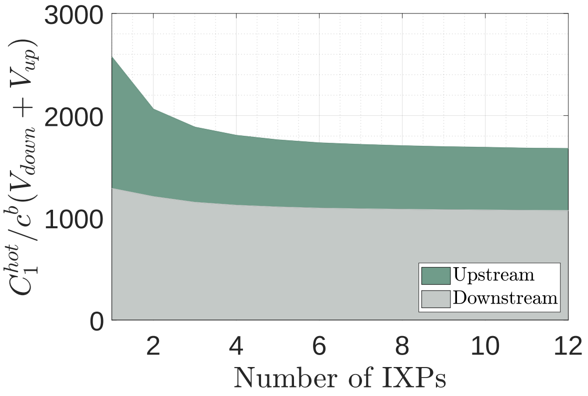
backbone when using cold potato routing. Thus, from (3.13), we know that:

$$ED^{b,hot}_{ana,up} = ED^{b,cold}_{ana,down} = 0 \tag{4.4}$$

The average distance the ISP carries upstream traffic across the backbone when using hot potato routing is zero because the ISP is exchanging this upstream traffic at the nearest IXP to the access network.



(a) $c^m/c^b = 1.5$



(b) $c^m/c^b = 3$

Figure 4.2: Total costs (analytical model)

Substituting the expression we previously found for ED_1^m in (3.15), we obtain:

$$C_{ana,up}^{hot} = c^m V_{up} \frac{abN}{LW} \sum_{m=1}^{\frac{W}{b}} \sum_{n=1}^{\frac{L}{aN}} \sqrt{\left(\frac{(2n-1)a - L/N}{2}\right)^2 + \left(\frac{(2m-1)b - W}{2}\right)^2} \tag{4.5}$$

Figure 4.2(a) shows the effect of the number of interconnection points (N) on the cost of both downstream ($C_{ana,down}^{hot}$) and upstream ($C_{ana,up}^{hot}$) traffic, when $c^m/c^b = 1.5$ and when there is an equal amount of downstream and upstream traffic (i.e., $V_{down} = V_{up}$). Figure 4.2(b) shows the same effect when the cost ratio $c^m/c^b = 3$.

We observe that, when the traffic ratio is 1:1, the cost is decreasing and convex with the number of interconnection points. We also observe that, over a wide range of cost ratios, there is less than a 2% difference in the cost between $N = 8$ and $N = 12$, so this indicates there may be little value in requiring interconnection at more than 8 IXPs.

We turn next to our numerical model, which we expect to be more accurate, albeit without closed-form expressions. The cost of downstream traffic is:

$$C^{hot}_{num,down} = c^b V_{down} ED^{b,hot}_{num,down} \tag{4.6}$$

where $ED^{b,hot}_{num,down}$ is given in (3.18).

The cost of upstream traffic is:

$$C^{hot}_{num,up} = c^b V_{up} ED^{b,hot}_{num,up} \tag{4.7}$$

where $ED^{b,hot}_{num,up} = ED^{b,cold}_{num,down}$, which is given in (3.21).

Figure 4.3 shows the effect of the number of interconnection points at which they peer (N) on the cost of both downstream and upstream traffic using hot potato routing. The cost ratio c^m/c^b is no longer relevant, as only the backbone traffic is affected. However, the number of interconnection points affects the backbone cost. The cost is the function of $\|IXP^{p,hot}_{num,down} - IXP^u_2\|$ and $\|IXP^{p,hot}_{num,up} - IXP^u_2\|$ for all IXPs. As the number of IXPs at which they peer increases, the IXP closest to the end user IXP^u_2 is fixed since it is related to the location of the end user and a deterministic function of U, namely $IXP^u_2 = (g' | U \in R^M_2(g'))$. However, $IXP^{p,hot}_{num,down}$ and $IXP^{p,hot}_{num,up}$ change.

IXP^s does depend on the number of IXPs at which they peer. The IXP at which traffic enters the ISP's network is the IXP closest to the source among the IXPs at which they agree to peer, i.e. $IXP^{p,hot}_{num,down} = (g| S \in R^N_2(g))$, and thus as the number of IXPs at which

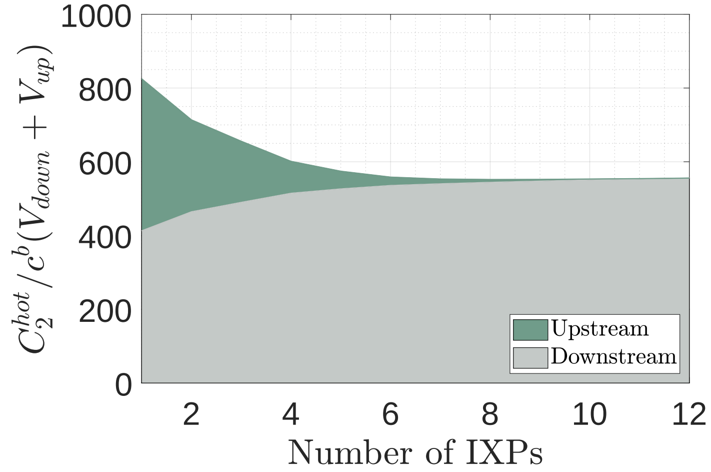


Figure 4.3: Total costs (numerical model)

they peer increases, $IXP^{p,hot}_{num,down}$ moves farther from IXP^u_2 and $\|IXP^{p,hot}_{num,down} - IXP^u_2\|$ increases. Thus, the downstream cost increases. The downstream cost is concave, because the incremental distance from $IXP^{p,hot}_{num,down}$ to IXP^u_2 associated with adding another IXP decreases, namely there are decreasing returns.

However, at the same time, the ISP exchanges upstream traffic using hot potato at the IXP closest to the end user at which the two ISPs agree to peer, i.e. $IXP^{p,hot}_{num,up} = (g|\, U \in R^N_2(g))$. Thus as the number of IXPs at which they peer increases, $IXP^{p,hot}_{num,up}$ moves closer to IXP^u_2 and $\|IXP^{p,hot}_{num,up} - IXP^u_2\|$ decreases. Therefore, the upstream cost decreases. The upstream cost is convex, because the incremental distance from IXP^u_2 to $IXP^{p,hot}_{num,up}$ associated with adding another IXP decreases, namely there are decreasing returns.

When the traffic ratio is 1:1, the decrease in the upstream cost exceeds the increase in the downstream cost. In the upstream route, $IXP^{p,hot}_{num,up}$ is the closest IXP to IXP^u_2, whereas, in the downstream route, $IXP^{p,hot}_{num,down}$ could be any IXP (including the closest or farthest IXP from IXP^u_2). Thus, as the number of IXPs increases, the absolute value of the slope of $\|IXP^{p,hot}_{num,up} - IXP^u_2\|$ in the upstream route is higher than the slope of $\|IXP^{p,hot}_{num,down} - IXP^u_2\|$ in the downstream route. It follows that the total cost decreases.

There are some differences between our results in our analytical and numerical models. The first difference is the middle mile cost. In our analytical model, the IXPs' locations vary with the number of interconnection points (see (3.2)), and thus the middle-mile cost, which varies with the distance between the access network and the closest IXP, decreases as the number of IXPs increases. However, in our numerical model, the number of IXPs at which both parties agree to interconnect does not affect the location of the IXP closest to the access network. Therefore, for fixed M, the middle mile cost is fixed. In Figure 4.2 for the analytical model, the upstream cost decreases but it does not decrease to zero, since the cost of the middle mile does not decrease to zero. However, in Figure 4.3 for the numerical model, the variable traffic-sensitive upstream cost decreases to zero, since the middle mile cost is fixed and the variable traffic-sensitive upstream backbone cost is zero at $N = M$, since there is no local delivery and thus no need to transfer traffic between IXPs.

The second difference is the traffic matrix. In our analytical model, we assume that incoming traffic is uniformly distributed over IXPs and that the population is distributed uniformly over the ISP's network. However, in our numerical model, we assume that the distribution of incoming traffic is related to the population of the region closest to an IXP and that end users are distributed across access networks according to the population of the county associated with the access network. Therefore, the slope decreases more quickly at a small number of IXPs (i.e., the second derivative is higher) in the numerical model than in the analytical model, because in the numerical model the ISP chooses an incremental IXP based on how much population would be affected by choosing that IXP.

We observe that, when the traffic ratio is 1:1, the cost is uni-modal with a minimum at $N = 8$. We also observe that there is less than a 2% difference in the cost between $N = 6$ and $N = 8$, so this indicates there may be little value in requiring interconnection at more than 6 IXPs. Based on Table 2.1, Charter, AT&T, and Verizon each require 6-8 IXPs for settlement-free peering.

We also wish to examine why ISPs require that the IXPs at which the two parties peer be selected from a specified list. To answer this question, our model selects the N IXPs at which to peer, from the list of $M = 12$ IXPs given in Table 2.2, so as to minimize its cost (C_2^{hot}):

$$I_2^N = \arg\min_{I_2^N} c^b \left(V_{down} ED^{b,hot}_{num,down} + V_{up} ED^{b,hot}_{num,up} \right) \tag{4.8}$$

The cost is typically minimized by selecting IXPs that span the country, so that the average distances the ISP carries traffic across its backbone are relatively small. Furthermore, when selecting a moderate or large number of IXPs, the cost is typically minimized by selecting more IXPs near where there are higher populations.

Comcast not only requires that potential settlement-free peering partners agree to peer at a minimum of 4 IXPs from Comcast's list of IXPs, it also requires that at least 1 of these 4 be on the west coast, that at least 1 be on the east coast, and that at least 1 be in a central region[58].[2] For $N = 4$, our numerical model chooses IXPs in Ashburn, Chicago, Los Angeles, and Atlanta, i.e. 1 on the west coast, 2 on the east coast, and 1 in the middle. All 4 of these cities are on Comcast's list.

Charter not only requires that potential settlement-free peering partners agree to peer at a minimum of 6-8 IXPs from Charter's list of IXPs[3], it also requires that at least 2 of these be in an eastern region, at least 2 be in a western region, and at least 2 be in a central region[59].[4] For $N = 8$, our numerical model chooses 4 on the east coast (Ashburn, New York, Miami, and Atlanta), 2 on the west coast (Los Angeles and Seattle), and 2 in the middle (Chicago and Dallas). All 8 of these cities are on Charter's list.

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[2] Comcast does not specify which IXPs are considered to be on the west coast, on the east coast, or in the central region. It also requires that the IXPs be "mutually agreeable".

[3] It requires a minimum of 6 IXPs when the 95th percentile of traffic exchanged is less 500 Gbps in the dominant direction, and it requires a minimum of 8 IXPs when it exceeds this threshold.

[4] Charter also specifies the IXPs in each of these regions.

Our numerical model thus not only explains why large ISPs require settlement-free peers to meet at a minimum of 4-8 IXPs, it also explains why these IXPs are geographically distributed across the country. Furthermore, it also predicts that more will typically be on the east coast, due to its greater population, than on the west coast or in the middle.

4.2 The Effect of Traffic Ratio

In this section, we examine the effect of the traffic ratio on the variable traffic-sensitive cost. Large ISPs often require that the ratio of incoming traffic to outgoing traffic remain below approximately 2:1. In the case of two interconnecting ISPs, we find that this requirement ensures a roughly equal exchange of value. Two networks will agree to settlement-free peering if and only if the arrangement is superior for both parties compared to alternative arrangements including paid peering and transit. The conventional wisdom is that settlement-free peering thus occurs if and only if the two parties perceive that they are gaining an approximately equal value from the arrangement. Furthermore, the conventional wisdom, when the two parties are both Tier 1 networks, is that the perceived value is related to the size of each network, the number of customers of each party, and the ratio of traffic exchanged in each direction.

Indeed, the settlement-free peering policies of large ISPs often place limits on the ratio of downstream traffic to upstream traffic. AT&T's settlement-free peering policy requires that this traffic ratio not exceed 2:1, and Verizon's settlement-free peering policy requires that this traffic ratio not exceed 1.8:1.[5]

In this section, we use our models to investigate the effect of the traffic ratio on the value to each interconnecting party, when the two parties are both ISPs. We use the variable traffic-

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[5] Some ISPs' settlement-free peering policies express an expectation of approximately equal value, but may not specify what this means, see e.g. Comcast [58].

sensitive cost as a proxy for value. Denote the ratio of downstream traffic to upstream traffic by $r = \frac{V_{down}}{V_{up}}$.

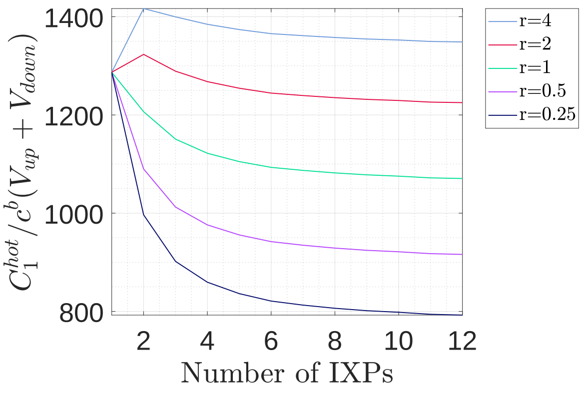
When using hot potato routing, the cost (C^{hot}) was plotted in Figures 4.2 and 4.3 for a traffic ratio of 1. For general traffic ratios, using the analytical model, we can derive the cost from (4.1), (4.3), and (4.4), as:

$$\begin{aligned} C_1^{hot} &= C_{ana,down}^{hot} + C_{ana,up}^{hot} \\ &= c^b(V_{down} + V_{up})\frac{rED_{ana,down}^{b,hot} + \frac{c^m}{c^b}(r+1)ED_1^m}{r+1} \end{aligned} \tag{4.9}$$

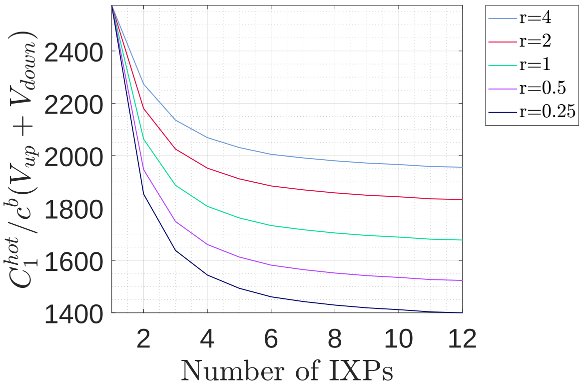
where $ED_{ana,down}^{b,hot}$ and ED_1^m are given in (3.12) and (3.15).

Figure 4.4(a) shows the effect of the traffic ratio on the cost, for various traffic ratios, when $c^m/c^b = 1.5$. The traffic ratio determines the trade-off between the downstream and upstream costs. For traffic ratios at or below 2:1, the variation in the upstream cost with the number of IXPs dominates, and thus interconnecting at 6 to 8 IXPs results in close to a minimum total cost. Requiring interconnection at more than 8 interconnection points is of little incremental value. However, for traffic ratios above 2:1, the variation in the downstream cost with the number of IXPs dominates, and it is rational for the ISP to not agree to settlement-free peering. The traffic ratios at which an ISP will perceive approximately equal value from peering depends on the difference in value it is willing to accept, and the alternatives it has to deliver and receive traffic.

Figure 4.4(b) shows the effect of the traffic ratio on the cost, for various traffic ratios, when the cost ratio is higher, at $c^m/c^b = 3$. For any traffic ratio, the variation in the middle mile cost dominates the backbone cost, and thus both downstream and upstream costs decrease as the number of IXPs increases. Therefore, the cost decreases as the number of IXPs increases for all plotted traffic ratios. As was true for a lower cost ratio, the requirement to peer at 6 to 8 interconnection points is reasonable, and requiring peering at more than 8 IXPs is of



(a) $c^m/c^b = 1.5$



(b) $c^m/c^b = 3$

Figure 4.4: Total costs for various traffic ratios (analytical model)

little incremental value.

Switching to the numerical model, we can derive the cost from (4.6) and (4.7), as:

$$\begin{aligned} C_2^{hot} &= C_{num,down}^{hot} + C_{num,up}^{hot} \\ &= c^b(V_{down} + V_{up})\frac{rED_{num,down}^{b,hot} + ED_{num,up}^{b,hot}}{r+1} \end{aligned} \tag{4.10}$$

Figure 4.5 shows the effect of the traffic ratio on the cost, for various traffic ratios using the numerical model. For traffic ratios at or below 2:1, the decrease in the upstream cost with the number of IXPs dominates the corresponding increase in the downstream cost, since

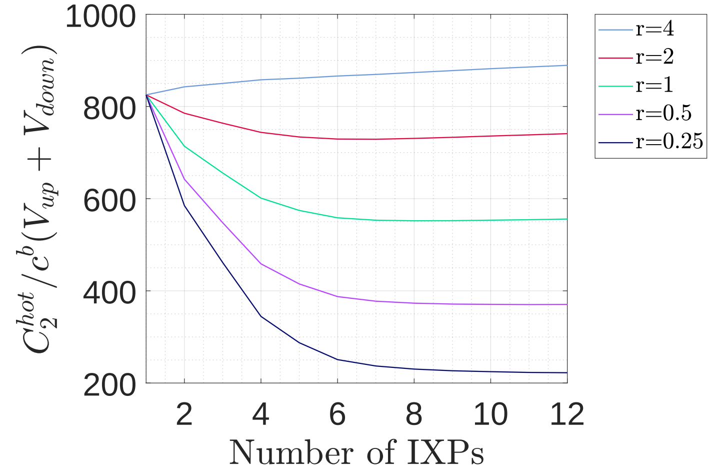


Figure 4.5: Total costs for various traffic ratios (numerical model)

the decrease in upstream cost due to *all* traffic exiting the ISP's network at a closer IXP outweighs the relatively small increase in downstream cost due to *some* traffic entering the ISP's network at a further away IXP. Recall that when the traffic ratio is 1:1, there is less than a 2% difference in the cost between $N = 6$ and the N at which cost is minimized, so there may be little value in requiring interconnection at more than 6 IXPs. We now find that when the traffic ratio is 0.5:1, there is less than a 2% difference in the cost between $N = 7$ and the N at which cost is minimized, and when the traffic ratio is 2:1, there is less than a 2% difference in the cost between $N = 4$ and the N at which cost is minimized.

In contrast, when the traffic ratio is 4:1, the increase in the downstream cost dominates the decrease in the upstream cost, since the downstream traffic volume is 4 times higher than the upstream traffic volume. As a result, the total cost increases with the number of IXPs at which they peer, and thus it is no longer rational for the ISP to agree to settlement-free peering.

In conclusion, the traffic ratios at which an ISP will perceive approximately equal value from peering depends on the difference in value it is willing to accept, and the alternatives it has to deliver and receive traffic. However, based on both models, we would expect the maximum acceptable traffic ratio to be 2:1 or less. Indeed, we observe that amongst the four largest ISPs, one specifies a maximum traffic ratio of 2:1, one specifies a maximum traffic ratio of 1.8:1, and one requires a “general balance” of traffic. In addition, we observe that for traffic ratios at or below 2:1, it remains rational to require interconnection at a minimum of 6-7 IXPs.

4.3 Traffic-sensitive Backbone Cost

When analyzing fair peering fees, it is necessary to define what we mean by *fair*. A large portion of an ISP’s costs are recovered from its subscribers. An ISP may, however, also recover some of its costs from interconnecting networks.

Our focus here is on traffic-sensitive costs, since the debate over paid peering centers on costs incurred because of traffic. However, we must still address whether an ISP should recover traffic-sensitive costs across different parts of its network solely from its subscribers or also from interconnecting networks.

Economists often debate about the proper amount of cost recovery from each side in two-sided markets. In the context of peering, however, there is general agreement that subscribers cover, at a minimum, the costs of an ISP’s access and middle-mile networks. The debate is generally over what portion of the costs of an ISP’s backbone networks should be borne by subscribers versus interconnecting networks.

There are several rationales for this approach. First, regulatory cost accounting often dictates that access network costs be recovered from subscribers. Second, the conditions under which two ISPs peer (including routing, number of interconnection points, and traffic ratios) affect ISPs’ backbone transportation costs. However, these same conditions do not affect ISPs’ middle-mile or access network transportation costs, since an ISP must carry traffic across these portions of its network regardless.

In the remainder of this dissertation, we thus focus on traffic-sensitive backbone costs. Therefore, in order to understand the effect of routing policies, traffic ratios, and traffic localization on peering agreements between two ISPs, we first analyze traffic-sensitive backbone costs.

When we refer to "traffic localization," we are describing the strategy wherein the peering network directs traffic to the IXP closest to the end user. This approach ensures that the ISP often avoids transporting the traffic across its backbone network, especially when they have a peering agreement at the nearest IXP to the end user. Even in situations where they don't peer at the closest IXP, the distance the ISP needs to cover to transport the traffic over its backbone is significantly reduced.

From now through this section, we will focus solely on the numerical model.

We consider two ISPs, denoted as ISP^1 hosting the end user (U) and ISP^2 where the source (S) is located. We assume that the two ISPs interconnect at the 12 major interconnection points, and that both use hot potato routing. We consider downstream traffic originating on ISP^2's network destined for an end user located in ISP^1's network[6], and denote the volume of this traffic by V^1_{down}. We also consider upstream traffic originating with an end user located in ISP^1's network and destined for a location on ISP^2's network, and denote the volume of this traffic by V^1_{up}. We denote the traffic ratio by $r^1 = \frac{V^1_{down}}{V^1_{up}}$.

We denote ISP^1's traffic-sensitive backbone cost by C^{ISP^1}, and partition it into the cost of delivering downstream traffic, which flows from the source S to the user U, denoted by $C^{ISP^1}_{S,U}$; and the cost of delivering upstream traffic, which flows from the user U to the source

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[6] We consider endpoints in an ISP's customer cone as equivalent to endpoints on an ISP's network, and do not explicitly consider payments between an ISP and it's transit customers.

S, denoted by $C_{U,S}^{ISP^1}$:

$$C^{ISP^1} = C_{S,U}^{ISP^1} + C_{U,S}^{ISP^1} \tag{4.11}$$

The backbone cost of delivering downstream traffic using hot potato routing is:

$$C_{S,U}^{ISP^1} = c^b V_{down}^1 ED_{num,down}^{b,hot}(M), \tag{4.12}$$

where c^b is the cost per unit distance and per unit volume in the backbone network, and $ED_{num,down}^{b,hot}(M)$ is the average distance on ISP^1's backbone network of downstream traffic with hot potato routing, when interconnecting at $M = 12$ IXPs.

The cost of delivering backbone upstream traffic using hot potato routing is:

$$\begin{aligned} C_{U,S}^{ISP^1} &= c^b V_{up}^1 ED_{num,up}^{b,hot}(M) \\ &= c^b V_{up}^1 ED_{num,down}^{b,cold}(M), \end{aligned} \tag{4.13}$$

because the average distance on ISP^1's backbone network of upstream traffic with hot potato routing, when interconnecting at $M = 12$ IXPs, is the same as the average distance on ISP^1's backbone network of downstream traffic with cold potato routing (i.e., $ED_{num,up}^{b,hot}(M) = ED_{num,down}^{b,cold}(M)$).

Since the two ISPs are assumed to interconnect at all $M = 12$ major interconnection points and are assumed to use hot potato routing for upstream traffic, it follows that $ED_{num,up}^{b,hot}(M) = ED_{num,down}^{b,cold}(M) = 0$. This occurs because, within our model's assumptions, when ISPs interconnect at all M IXPs and apply hot potato routing for upstream traffic, they effectively do not carry the traffic across their own backbone network. The traffic is instead offloaded immediately at the closest peering point, which results in no additional distance being traversed on the ISP's backbone network.

As a result, equations (4.11)-(4.13) can be simplified to:

$$C^{ISP^1} = c^b V^1_{down} ED^{b,hot}_{num,down}(M) \tag{4.14}$$

Using similar calculations and the definition of the traffic ratio r^1, the backbone cost of ISP^2 is:

$$\begin{aligned} C^{ISP^2} &= c^b V^2_{down} ED^{b,hot}_{num,down}(M) \\ &= c^b V^1_{up} ED^{b,hot}_{num,down}(M) = c^b \frac{V^1_{down}}{r^1} ED^{b,hot}_{num,down}(M) \end{aligned} \tag{4.15}$$

4.4 Fair Peering Fee

We first examine the conditions under which the two ISPs would agree to settlement-free peering. We assume here that they will agree to settlement-free peering if and only if they incur the same amount of traffic-sensitive backbone costs.[7] Not surprisingly, the two ISPs incur the same backbone cost (i.e., $C^{ISP^1} = C^{ISP^2}$) if and only if the traffic ratio is 1.

We next examine the fair peering fee when the traffic ratio is not 1. Now, in order to equalize net costs, the ISP with a lower traffic-sensitive backbone cost should compensate the other ISP. Denote the fee that ISP^2 pays ISP^1 for peering by P^{ISP^2,ISP^1}. The peering fee that equalizes net costs is given by:

Theorem 4.1. *The fair peering fee between two ISPs is:*

$$P^{ISP^2,ISP^1} = \frac{1}{2} c^b (V^1_{down} - V^1_{up}) ED^{b,hot}_{num,down}(M) \tag{4.16}$$

The proof can be found in the Appendix D.

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[7] That said, we note that two ISPs may agree to settlement-free peering only if they obtain roughly equal value from the arrangement, and value may not be dictated solely by cost sharing. In particular, we do not consider market power.

Theorem 4.1 states that the peering fee that equalizes net costs is one half of the difference between the costs incurred by the two ISPs. If the traffic ratio is greater than 1, then the fair peering fee is positive, and if the traffic ratio is less than 1, then the fair peering fee is negative. However, when the traffic ratio is close to 1 (e.g., between 0.5 and 2), then the fair peering fee may be small, and hence the ISPs may choose to adopt settlement-free peering regardless.

Chapter 5

Peering Between A Transit Provider And An ISP

We now turn to peering between a transit provider and an ISP, i.e., neither is a customer of the other. In this section, we consider the traffic-sensitive backbone costs of each and determine the fair peering fee.

In this section, the terms "hot potato" routing and "cold potato" routing refer to the routing decisions made by the network provider where the originating source of the traffic is located. In hot potato routing, the network provider prefers to offload traffic to the destination network as quickly as possible, typically at the closest available interconnection point. This strategy helps the network provider minimize its own cost by avoiding long-distance data transport. On the other hand, cold potato routing involves the network provider holding onto outgoing traffic for longer distances before handing it off to the destination network.

Transit providers that sell transit services to content providers often promise the content provider that they will deliver the traffic to the terminating ISP using cold potato routing. The use of cold potato routing allows the transit provider to exercise greater control over the management of this traffic and thereby to potentially improve its Quality of Service (QoS). Most of this content consists of video, and in the remainder of the dissertation, we use the term *video* to refer to it.

We partition traffic exchanged between a transit provider and an ISP into video traffic and non-video traffic. We assume that non-video traffic is transported using hot potato routing. We assume that a proportion x of video traffic transmitted to the ISP's users within each access network is delivered from the transit provider using cold potato routing. We assume that the transit provider and the ISP interconnect at all $M = 12$ IXPs, and consequently, that video traffic delivered using cold potato routing is exchanged at the IXP closest to the end user. We assume that the remaining proportion $1 - x$ of video traffic is delivered using hot potato routing and that the source of this video traffic is independent of the location of the end user.

Our focus here is on traffic-sensitive costs, since they are the focus of the debate on paid peering. To analyze fair peering fees, we must define *fair* and decide if traffic-sensitive costs should be recovered from subscribers or from interconnecting networks. Economists debate how to divide costs in this two-sided market, but generally agree that subscribers should cover access and middle-mile network costs. There are several rationales for this approach. First, regulatory cost accounting often dictates that access network costs be recovered from subscribers. Second, the conditions under which two networks peer affect ISPs' backbone transportation costs. However, these same conditions do not affect ISPs' middle-mile or access network transportation costs, since an ISP must carry traffic across these portions of its network regardless. The debate is thus over how much of the backbone network costs should be paid by subscribers versus by interconnecting networks. In the remainder of the dissertation, we thus focus on traffic-sensitive backbone costs.

In this section, we will focus solely on the numerical model.

5.1 Backbone Costs for Peering Between a Transit Provider and an ISP

We now turn to peering between a transit provider and an ISP, i.e., neither is a customer of the other. In this section, we consider the traffic-sensitive backbone costs of each. In the following section, we determine the fair peering fee.

Consider the case in which neither the ISP nor the transit provider is a customer of the other. Rather, they agree to peer with each other. Peering between a transit provider and an ISP is different than peering between two ISPs for two reasons. First, transit providers increasingly carry not only traffic indirectly passing from one ISP to another, but also content provider traffic. In this case, the ratio of downstream traffic (from the transit provider to the ISP) to upstream traffic (from the ISP to the transit provider) is likely to be higher than when two ISPs interconnect, because the content provider traffic is almost entirely downstream video traffic. The higher traffic ratio increases the ISP's backbone transportation costs.

Second, the transit provider may deliver a portion of the video traffic using cold potato routing, which localizes traffic on the ISP's network and reduces the ISP's backbone transportation costs. Cold potato routing is one such strategy that is commonly employed by transit providers, particularly when delivering video content. This routing method allows the transit provider to retain control over a larger portion of the traffic's journey, potentially leading to improvements in Quality of Service (QoS).

In this section, we model both the ISP's and the transit provider's backbone transportation costs, as a function of the number of interconnection points and the traffic ratio between the two, routing, and localization. We wish to understand how traffic ratios and video traffic localization could impact the backbone cost of each network.

5.1.1 Localization and Routing

We partition traffic exchanged between a transit provider and an ISP into video traffic and non-video traffic. As before, we assume that non-video traffic is transported using hot potato routing.

However, for video traffic, we assume that a portion is delivered from the transit provider to the ISP using cold potato routing. Specifically, we assume that a proportion x of the video traffic transmitted to the ISP's users within each access network is delivered from the transit provider using cold potato routing. We assume that the transit provider and the ISP interconnect at all $M = 12$ major interconnection points, and consequently, that video traffic delivered using cold potato routing is handed off from the transit provider to the ISP at the IXP closest to the end user. We assume that the remaining proportion $1 - x$ of the video traffic transmitted to the ISP's users within each access network is delivered using hot potato routing, and that the source of this video traffic is independent of the location of the end user.

5.1.2 ISP Backbone Cost

We consider downstream traffic destined for an end user located in the ISP's network. We denote the volume of non-video downstream traffic by V_{down}^{nv} and the volume of video downstream traffic by V_{down}^{v} ($V_{down} = V_{down}^{nv} + V_{down}^{v}$). We also consider upstream traffic originating with an end user located in the ISP's network, and denote the volume of this traffic by V_{up}.

We define two traffic ratios: $r^{nv} = \frac{V_{down}^{nv}}{V_{up}}$, the ratio of downstream non-video traffic to upstream traffic, and $r^{v} = \frac{V_{down}^{v}}{V_{up}}$, the ratio of downstream video traffic to upstream traffic.

When an ISP interconnects at M IXPs with another transit provider, incorporating x percentage of localization, we denote the ISP's traffic-sensitive backbone cost by $C_{(ISP-TP,M,x)}^{ISP}$, and partition it into the cost of delivering downstream non-video traffic, which flows from the source S to the user U, (denoted by $C^{ISP}_{S,U,non-video}$), the cost of delivering downstream video traffic, which flows from the source S to the user U, (denoted by $C^{ISP}_{S,U,video}$), and the cost of delivering upstream traffic, which flows from the user U to the source S, (denoted by $C^{ISP}_{U,S}$):

Theorem 5.1. *The traffic-sensitive backbone cost of the ISP when peering with the transit provider is:*

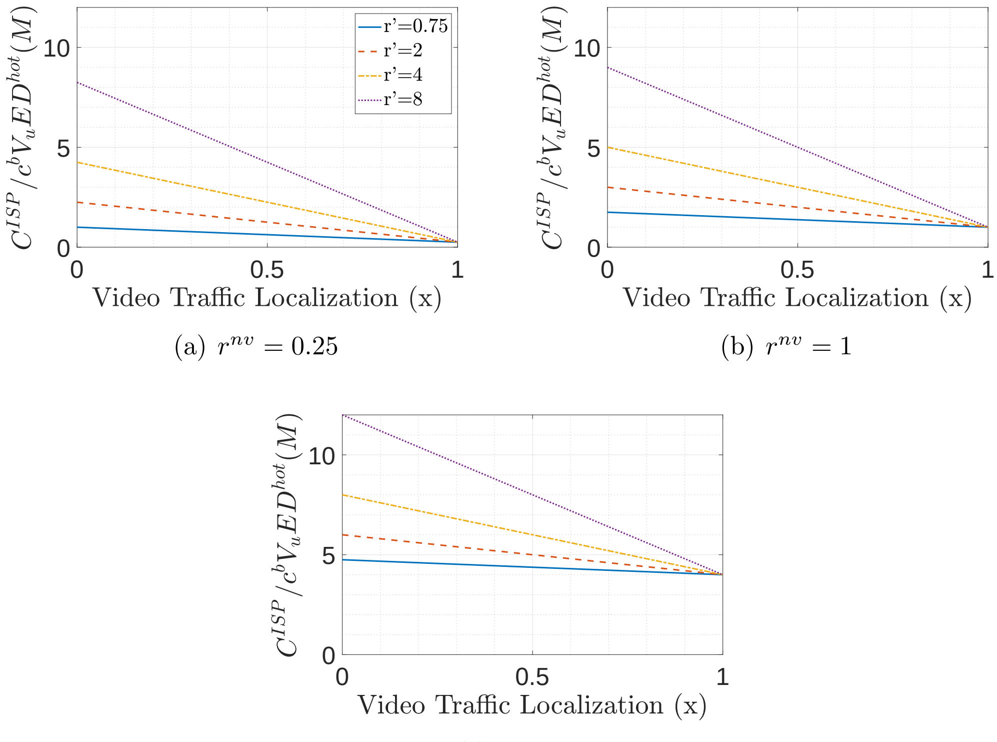
$$\begin{aligned} C^{ISP}_{(ISP-TP,M,x)} &= c^b \Big[V^{nv}_{down} + V^{v}_{down}(1-x)\Big] ED^{b,hot}_{num,down}(M) \\ &= c^b V_{up} \Big[r^{nv} + r^{v}(1-x)\Big] ED^{b,hot}_{num,down}(M) \end{aligned} \tag{5.1}$$

The proof can be found in the Appendix E.

A portion of the ISP's backbone cost is caused by the need to transport downstream non-video traffic over the ISP's backbone, as measured by the volume V^{nv}_{down} of such traffic. Another portion of the ISP's backbone cost is caused by the need to transport downstream non-localized video traffic over the ISP's backbone, as measured by the volume $V^{v}_{down}(1-x)$ of such traffic.

Figure 5.1 illustrates the normalized ISP backbone cost for different traffic ratios and video traffic localization. For fixed traffic ratios (r^{nv} and r^{v}), the normalized ISP backbone cost is decreasing with the amount of video traffic localization (x), because increasing localization results in the transit provider carrying more of the video traffic on its backbone network and handing it off to the ISP at an IXP closer to end users.

For fixed non-video traffic ratio (r^{nv}) and fixed video traffic localization (x), the normalized ISP backbone cost is increasing with the video traffic ratio (r^{v}), because as video traffic increases, the ISP needs to carry more video traffic on its backbone. However, the amount of the increase in ISP backbone cost due to increased video traffic lessens as video traffic



(a) $r^{nv} = 0.25$ (b) $r^{nv} = 1$

(c) $r^{nv} = 4$

Figure 5.1: ISP Backbone Cost

localization increases, because the ISP does not need to carry as much video traffic over long distances.

Finally, for fixed video traffic ratio (r^v) and fixed video traffic localization (x), the normalized ISP backbone cost is increasing with the non-video traffic ratio (r^{nv}), because the ISP needs to carry more non-video downstream traffic on its backbone.

5.1.3 Transit Provider Backbone Cost

We now turn to the effect of routing policies, traffic ratios, and traffic localization on the traffic-sensitive backbone cost of the transit provider.

Note that downstream traffic from the point of view of the transit provider (traffic entering the transit provider's network) is equal to the upstream traffic from the point of view of the ISP (traffic leaving the ISP's network) (V_{up}). Similarly, the transit provider non-video upstream traffic is equal to ISP non-video downstream traffic (V^{nv}_{down}), and the transit provider video upstream traffic is equal to ISP video downstream traffic (V^{v}_{down}).

When an ISP interconnects at M IXPs with another transit provider, incorporating x percentage of localization, we denote the transit provider's traffic-sensitive backbone cost by $C^{TP}_{(ISP-TP,M,x)}$, and partition it into the transit provider's downstream cost for delivering ISP upstream traffic, which flows from the user U to the source S, (denoted by $C^{TP}_{U,S}$), its upstream cost for delivering ISP downstream non-video traffic, which flows from the source S to the user U, (denoted by $C^{TP}_{S,U,non-video}$), and its upstream cost for delivering ISP downstream video traffic, which flows from the source S to the user U, (denoted by $C^{TP}_{S,U,video}$):

Theorem 5.2. *The traffic-sensitive backbone cost of the transit provider when peering with the ISP is:*

$$\begin{aligned} C^{TP}_{(ISP-TP,M,x)} &= c^b(V_{up} + V^{v}_{down}x)ED^{b,hot}_{num,down}(M) \\ &= c^b V_{up}(1 + r^v x)ED^{b,hot}_{num,down}(M) \end{aligned} \tag{5.2}$$

The proof can be found in the Appendix F.

A portion of the transit provider's backbone cost is caused by the need to transport the ISP's upstream traffic over the transit provider's backbone, as measured by the volume V_{up} of such traffic. Another portion of the transit provider's backbone cost is caused by the need to transport ISP downstream localized video traffic over the transit provider's backbone, as measured by the volume $V^{v}_{down}x$ of such traffic.

Figure 5.2 illustrates the normalized transit provider backbone cost for different video traffic ratios and video traffic localization. For a fixed video traffic ratio (r^v), the normalized transit provider backbone cost is increasing with the amount of video traffic localization (x), because

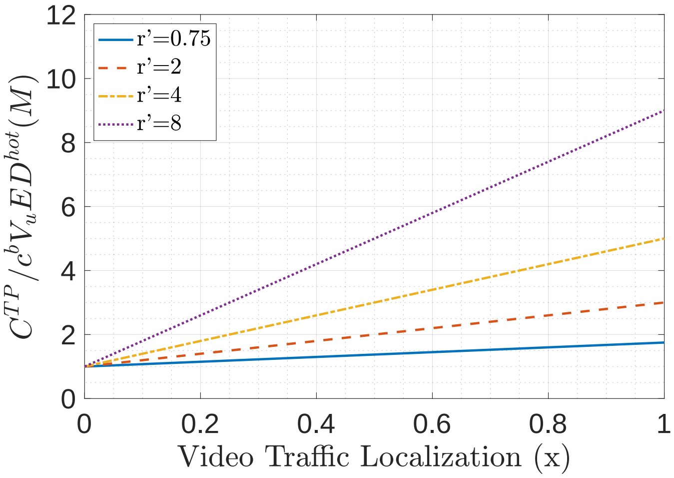


Figure 5.2: Transit Provider Backbone Cost

increasing localization results in the transit provider carrying more of the video traffic on its backbone network and handing it off to the ISP at an IXP closer to end users.

For fixed video traffic localization (x), the normalized transit provider backbone cost is increasing with the video traffic ratio (r^v), because as video traffic increases, the transit provider needs to carry more video traffic on its backbone. In addition, the amount of the increase in transit provider backbone cost due to increased video traffic increases as video traffic localization increases, because the transit provider needs to carry more video traffic over long distances.

The cost of the transit provider is normalized to the upstream traffic, so it remains constant with changes in the non-video traffic ratio (r^{nv}), as the transit provider is only responsible for carrying the ISP upstream traffic on its backbone. Therefore, the figure is independent of r^{nv}.

So far, we analyzed the effect of routing policies, traffic ratios, and traffic localization on the traffic-sensitive backbone costs incurred by an ISP and a transit provider. We found that as video traffic localization increases, the transit provider carries an increasing amount of the video traffic across its network and hands it off closer to end-users, leading to a decrease in the ISP's cost and an increase in the transit provider's cost. Moreover, for a fixed percentage of video traffic localization, as the volume of video traffic increases, the costs incurred by the ISP and the transit provider both increase, since they both need to transport more video traffic on their backbones. The increase in cost is more pronounced for the ISP when the traffic localization is low, due to the longer distances that the ISP must transport the traffic on its backbone. Similarly, the increase in cost is more pronounced for the transit provider when the traffic localization is high, because the transit provider must carry the traffic over longer distances on its backbone. In addition, the impact of the imbalance in non-video traffic between the ISP and the transit provider also affects the ISP's cost share; as the ratio of non-video downstream traffic to upstream traffic increases, the ISP's cost share increases.

5.2 Peering Fee Between a Transit Provider and an ISP

In the previous section, we analyzed the traffic-sensitive backbone costs of the ISP and the transit provider. In this section, we determine the fair peering fee between the ISP and the transit provider. When analyzing peering between two ISPs, we defined *fair* as the peering fee that equalized the net cost to each ISP. Here, when analyzing peering between an ISP and a transit provider, again we set the peering fee to equalize the net cost to each.

We consider three different scenarios based on how the transit provider delivers the traffic. First, we examine the case where the transit provider delivers the traffic with hot potato routing. Second, we explore the scenario in which the transit provider delivers part of the video traffic with cold potato routing, which localizes the traffic on the ISP's network. Finally, we consider the case where the transit provider uses a CDN to deliver part of the video traffic instead of delivering it with cold potato routing. Through these scenarios, we investigate the impact of different methods of delivering traffic on the cost-sharing arrangements between the ISP and the transit provider.

5.2.1 Fair Peering Fee with Hot Potato Routing

Recall that we denote the volume of non-video downstream traffic by V_{down}^{nv}, the volume of video downstream traffic by V_{down}^{v}, and the volume of upstream traffic by V_{up}. We also define two traffic ratios: $r^{nv} = \frac{V_{down}^{nv}}{V_{up}}$, the ratio of downstream non-video traffic to upstream traffic, and $r^{v} = \frac{V_{down}^{v}}{V_{up}}$, the ratio of downstream video traffic to upstream traffic. In this section, we assume the transit provider delivers all downstream traffic using hot potato routing.

The ISP's traffic-sensitive backbone cost is determined solely by the locations of the IXPs at which traffic is exchanged, the routing of the traffic, and the volume of the traffic. Thus, it follows that the fair peering fee between the ISP and the transit provider is still determined by equalizing their net costs, as was done in Theorem 4.1 for the case of two peering ISPs, except that we must now account for the added video traffic:

$$P^{TP,ISP} = \frac{1}{2}c^{b}(V_{down}^{nv} + V_{down}^{v} - V_{up})ED_{num,down}^{b,hot}(M) \tag{5.3}$$

The added video traffic results in a higher fair peering fee than would be the case of peering between two ISPs that did not include the exchange of this video traffic.

5.2.2 Fair Peering Fee with Cold Potato Routing

Transit providers that sell transit services to content providers often promise the content provider that they will deliver the traffic to the terminating ISP using cold potato routing. The use of cold potato routing allows the transit provider to exercise greater control over the management of this traffic and thereby potentially improve its Quality of Service (QoS). Most of this content consists of video, and in the remainder of the dissertation, we use the term *video* to refer to it.

We consider the scenario in which the transit provider delivers part of the video traffic with cold potato routing, which localizes the traffic on the ISP's network. Specifically, we assume that a proportion x of the video traffic transmitted to the ISP's users within each access network is delivered from the transit provider using cold potato routing. We assume that the remaining proportion $1-x$ of the video traffic transmitted to the ISP's users within each access network is delivered using hot potato routing, and that the source of this video traffic is independent of the location of the end user. We also assume that the transit provider delivers the non-video traffic using hot potato routing.

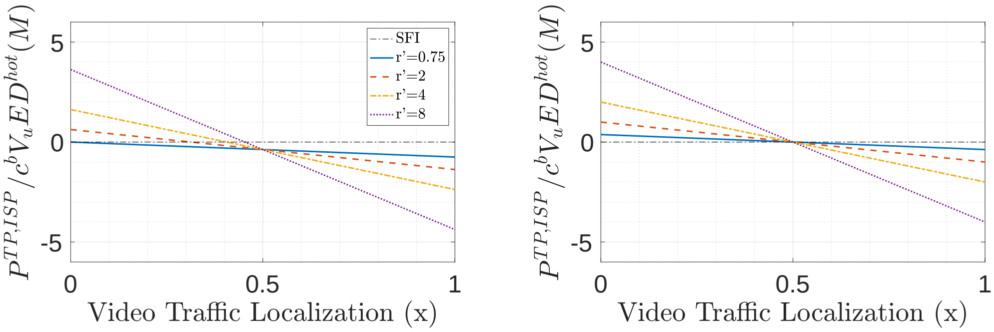
We focus on the cost-sharing framework between the ISP and the transit provider. Our objective is to establish a system that ensures both parties incur the same costs for transmitting data over their backbones. To achieve this goal, we use the analysis of the cost structures of ISPs and transit providers that we provided in the previous section, and calculate the payment required to ensure that the costs are fairly split between the two parties. The peering fee that equalizes net costs is given by:

Theorem 5.3. *The fair peering fee between the transit provider and the ISP is:*

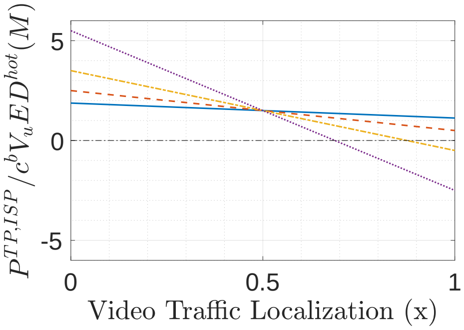
$$P^{TP,ISP} = c^b V_{up}\Big[\frac{1}{2}(r^{nv}-1) + r^v(0.5-x)\Big] ED^{b,hot}_{num,down}(M) \tag{5.4}$$

The proof can be found in the Appendix G.

Figure 5.3 illustrates the normalized fair peering fee for different traffic ratios and video traffic localization. As the transit provider localizes an increasing percentage of video traffic, the fair peering fee decreases, reflecting the transit provider's increased cost and the ISP's decreased cost. Indeed, at high enough percentages of video traffic localization, the fair peering fee becomes negative, meaning that equalizing net cost requires the ISP to pay the transit provider (not vice versa). The slope at which the fair peering fee decreases with increasing video traffic localization becomes steeper at higher volumes of video traffic (i.e.,



(a) $r^{nv} = 0.25$ (b) $r^{nv} = 1$



(c) $r^{nv} = 4$

Figure 5.3: Fair Peering Fee Between a Transit Provider and an ISP

higher video traffic ratios r^v), reflecting a greater sensitivity of costs to the volume of video traffic. When video traffic localization is less than 50%, the fair peering fee increases with the volume of video traffic, since the transit provider sends more video traffic to the ISP without contributing much to its transportation cost. In contrast, when video traffic localization is more than 50%, the fair peering fee decreases as the amount of video traffic increases, since the transit provider contributes more to the cost of transporting this video across the backbone than does the ISP. Finally, for a fixed percentage of video traffic localization, the fair peering fee increases with the non-video traffic ratio r^{nv}, reflecting the ISP's increased cost.

5.2.3 Settlement-Free Peering

Recall that when two ISPs peer, the fair peering fee is zero (i.e., settlement-free peering) when the traffic ratio $r^{nv} = 1$. In contrast, when a transit provider peers with an ISP, this is no longer the case. Now, absent any localization of video traffic, the fair peering fee is zero only if the combined traffic ratio $r^{nv} + r^v = 1$. If the transit provider carries a substantial amount of video traffic, this is likely to result in a positive fair peering fee. However, the transit provider can reduce the fair peering fee by localizing a portion of the video traffic. The percentage of video traffic localization that equalizes the transit provider's and ISP's backbone costs is given by:

Theorem 5.4. *The percentage of video traffic localization between a transit provider and an ISP required for a fair peering fee of zero is:*

$$x = \frac{r^{nv} + r^v - 1}{2r^v} \tag{5.5}$$

The proof can be found in the Appendix H.

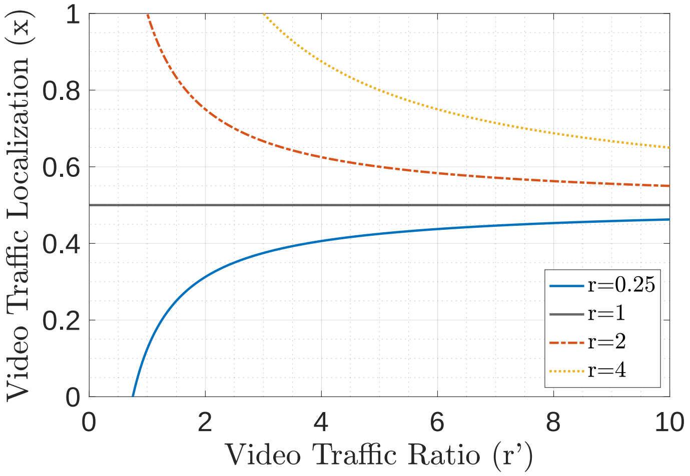


Figure 5.4: Settlement-Free Peering Curve Between a Transit Provider and an ISP

Figure 5.4 illustrates the amount of video traffic localization required for a fair peering fee of zero, as a function of the non-video traffic ratio r^{nv} and the volume of video traffic (reflected by the video traffic ratio r^{v}). This settlement-free peering curve is determined by the relative costs incurred by the ISP and the transit provider.

When the non-video traffic ratio $r^{nv} = 1$, the volume of upstream and non-video downstream traffic is the same for both the ISP and the transit provider, resulting in both parties incurring equal non-video traffic-sensitive backbone costs. However, the addition of one-way video traffic sent via hot potato routing would impose extra costs on the ISP, which should be reimbursed through a positive peering fee. In order for the transit provider to achieve equal cost sharing with the ISP for the video traffic, it must localize 50% of that traffic. If the transit provider localizes less than 50% of the video traffic, the ISP incurs more backbone costs than does the transit provider, and consequently, compensation from the transit provider is warranted. Conversely, if the transit provider localizes more than 50% of the video traffic, the transit provider incurs more backbone costs than does the ISP, and consequently compensation from the ISP is warranted.

In contrast, when the non-video traffic ratio $r^{nv} < 1$, if there were no video traffic, the transit provider would incur more cost than the ISP, and consequently, the fair peering fee would be negative (i.e., the ISP should pay the transit provider). However, if there is a significant amount of video traffic sent via hot potato routing (e.g., $r^v \approx 0.75$ and $x = 0$), then the ISP cost to transport this video across its backbone can compensate for the unequal non-video traffic ratio (e.g., $r^{nv} = 0.25$), and result in settlement-free peering. As the volume of video traffic increases, in order to maintain equal net costs, the transit provider needs to start to localize some of the video traffic, i.e., the settlement-free peering curve is increasing with the volume of video traffic (as reflected by a higher video traffic ratio r^v). The curve is concave and has an asymptote at $x = 0.5$, because even at arbitrarily high video traffic volumes, 50% localization is sufficient to entitle the transit provider for settlement-free peering. Indeed, it can be readily seen from Theorem 5.4 that $x \to 0.5$ as $r^v \to \infty$.

Finally, when the non-video traffic ratio $r^{nv} > 1$, if there were no video traffic, the ISP would incur more cost than the transit provider, and consequently, the fair peering fee would be positive (i.e., the transit provider should pay the ISP). If there is video traffic but the transit provider transports it with less than 50% localization, the cost burden on the ISP increases even more since the ISP incurs more cost to transmit this video than does the transit provider; hence, the transit provider should pay the ISP for both the high non-video traffic ratio and the imbalance in the cost of carrying video traffic. On the other hand, if the transit provider highly localizes video traffic, the transit provider may be eligible for settlement-free peering. For example, when $r^{nv} = 2$, if $r^v = 1$ and $x = 1$, then the transit provider cost to transport this video across its backbone can compensate for the unequal non-video traffic ratio, and result in settlement-free peering. As the volume of video traffic increases, then in order to maintain equal net costs, the transit provider needs less localization, i.e., the settlement-free peering curve is decreasing with the volume of video traffic (as reflected by a higher video traffic ratio r^v). The curve is convex and has an asymptote at $x = 0.5$.

5.2.4 Transit Provider Using CDNs

In this section, we explore a scenario where the transit provider decides to implement Content Delivery Networks (CDNs) instead of carrying video traffic across its network using cold potato routing.

Assume that the non-video traffic ratio r^{nv} and the video traffic ratio r^{v} are fixed, and that the transit provider decides to localize a proportion x of the video traffic by transporting across its backbone using cold potato routing. Suppose that the ISP and the transit provider agree to the fair peering fee, as given in Theorem 5.3.

Now suppose that instead of localizing a proportion x of the video traffic by transporting across its backbone using cold potato routing, the transit provider places this same video traffic on a CDN instead of delivering it using cold potato routing. Specifically, we assume that a proportion x of the video traffic transmitted to the ISP's users within each access network is delivered from the transit provider at a CDN located at the IXP nearest to the end user. We assume that the remaining proportion $1 - x$ of the video traffic transmitted to the ISP's users within each access network is delivered using hot potato routing, and that the source of this video traffic is independent of the location of the end user.

By using a CDN, the transit provider reduces its traffic-sensitive backbone cost by:

$$\Delta C^{TP} = c^{b} V^{v}_{down} x ED^{b,hot}_{num,down}(M) \tag{5.6}$$

The result follows from Theorem 5.2.

However, in order to build the CDN, the transit provider incurs a cost which we denote by $Cost^{CIC}_{tp}$. If $Cost^{CIC}_{tp} < \Delta C^{TP}$, the transit provider may be incentivized to build the CDN. However, the question arises whether building the CDN will affect the fair peering fee. Indeed, the ISP may assert that it should share in a portion of the cost savings by increasing the fair peering fee.

We reject the notion that building the CDN should affect the fair peering fee. If the fair peering fee is not affected, then the transit provider will make a decision based solely upon a comparison between the cost of implementing CDNs with the cost of carrying traffic using cold potato routing:

Theorem 5.5. *The transit provider can achieve cost savings by implementing CDNs at M interconnection points with x percent of localization, if the cost of implementation is lower than the potential savings:*

$$Cost_{tp}^{CIC} < \Delta C^{TP} = c^b V_{down}^v x ED_{num,down}^{b,hot}(M) \tag{5.7}$$

This comparison of the cost of servers versus transmission is a classical engineering tradeoff. In contrast, if the fair peering fee were to be increased in order to share some of the cost savings with the ISP, then it would reduce the incentive of the transit provider to build a CDN, resulting in an inefficient architecture. In addition, we note that without a change in the fair peering fee, the ISP's net costs are unchanged.

5.2.5 Evaluation of Arguments

Our results contradict the manner in which large ISPs often portray the situation. Large ISPs often assert that the fair peering fee is positive whenever the combined traffic ratio $r^{nv}+r^v > 1$ regardless of the amount of localization. In contrast, we find that from Theorem 5.4 that when $r^{nv} + r^v > 1$, the fair peering fee is positive if and only if $x < \frac{r^{nv}+r^v-1}{2r^v}$. For example, if $r^{nv} = 1$, then a positive peering fee is only warranted if $x < 0.5$. In addition, large ISPs often assert that the fair peering fee increases monotonically with $r^{nv} + r^v$ regardless of the amount of localization. We do find that when video traffic localization is low, the fair peering fee increases monotonically with $r^{nv} + r^v$. However, for high levels of localization, the fair peering fee decreases with $r^{nv} + r^v$, since the transit provider incurs most of the backbone transportation cost.

Our results also partially contradict the manner in which transit providers often portray the situation. Transit providers often assert that they should be entitled to settlement-free peering if they provide sufficient localization of traffic. Although we find that this is true when the non-video traffic ratio $r^{nv} < 1$, for high non-video traffic ratios (e.g., $r^{nv} = 4$), even 100% localization of video traffic may not be sufficient unless the transit provider also localizes non-video traffic.

In this section, we analyzed the fair fee for peering between a transit provider and an ISP. If the transit provider uses hot potato routing for all traffic, then the fair peering fee is given by (5.3), which states that it is a function of the imbalance between all download traffic ($V^{nv}_{down} + V^{v}_{down}$) and upload traffic ($V_{up}$).

If the transit provider uses cold potato routing for a proportion x of the video traffic, then the fair peering fee is given by Theorem 5.3. The fair peering fee increases with the non-video traffic ratio r^{nv} and decreases with the proportion x. It also decreases more rapidly with x for higher video traffic volumes. The transit provider should pay the ISP for peering if it doesn't localize a sufficient portion of the video traffic. The fair peering fee may be positive and substantial if there is a high volume of video traffic with low localization.

The amount of localization that equalizes net costs is given by Theorem 5.4. Settlement-free peering is appropriate when the transit provider localizes a sufficient proportion of video traffic. The required proportion is less than 0.5 when the non-video traffic ratio $r^{nv} < 1$, equal to 0.5 when the non-video traffic ratio $r^{nv} = 1$, and greater than 0.5 when the non-video traffic ratio $r^{nv} > 1$.

Finally, we argue that the fair peering fee should be unchanged if the transit provider uses a

CDN to localize traffic instead of delivering it using cold potato routing. If so, a CDN will result in cost savings if the cost of building it is less than the cost of carrying traffic across the transit provider's backbone.

Chapter 6

Cost-Based Peering Between A Content Provider And An ISP

We now turn to peering between a content provider and an ISP. Settlement-free peering policies were originally constructed for peering between two Tier 1 ISPs. However, it has become common for large content providers to peer with ISPs. We call this the ISP-CP case. It is not clear the degree to which the settlement-free peering requirements discussed before should apply to the ISP-CP case.

Large ISPs do not generally have different settlement-free peering policies for content providers than for ISPs and transit providers. In addition, they have often asserted that content providers should meet the same requirements on the number of interconnection points and traffic ratio to qualify for settlement-free peering. We determine the conditions under which a content provider should be eligible for settlement-free peering. We will show that if a content provider delivers traffic to the ISP locally, then a requirement to interconnect at a minimum number of interconnection points is rational, but a limit on the traffic ratio is not rational. We will also show that if a content provider does not deliver traffic locally, the ISP is unlikely to perceive sufficient value to offer settlement-free peering.

Then, we compare such direct interconnection with the ISP with the indirect interconnection considered in the previous section, in which a content provider sends video traffic through a transit provider to the ISP. We focus on the impact of elements of peering policies, including the number of interconnection points and video traffic localization, on the fair peering fee.

In addressing ISP-content provider peering, our analysis remains neutral to the content provider's network topology. We focus on calculating a fair peering fee based only on the ISP's costs, which are influenced by interconnection points and traffic localization, not by whether the content provider uses its own backbone or a CDN. This ensures that our determination of a fair peering fee is consistent regardless of the content provider's infrastructure.

We assume that both the ISP and the content provider have agreed to peer with each other, however, peering between a content provider and an ISP differs from peering between a transit provider and an ISP for three reasons. First, we assume that the content provider has deployed content servers at N major interconnection points, and that N may be less than the number of interconnection points at which the transit provider and the ISP agree to peer (M). This could increase the ISP's backbone cost.

Second, the content provider may localize a different proportion of video traffic than does the transit provider, which may impact the ISP's backbone cost. A higher degree of localization may reduce the backbone costs for the ISP. We assume that a proportion x^d of the video transmitted to the ISP's users within each access network is delivered from the content provider at a server located at the IXP nearest to the end user among the IXPs at which they agree to peer. We assume that the remaining proportion $1-x^d$ of the video transmitted to the ISP's users within each access network is delivered using any content provider server, and that the location of this content provider's server is independent of the location of the end user.

Third, content providers carry only video traffic, which results in a higher ratio of downstream traffic (from the content provider to the ISP) to upstream traffic (from the ISP to the content provider) compared to transit providers. This is due to the fact that video traffic is almost entirely downstream. We denote the volume of video downstream traffic by V_v.

6.1 ISP Backbone Cost Under No Content Replication

We first consider a content provider that does not replicate its content and delivers traffic using hot potato routing.

The ISP network topology remains the same as was presented in Section 3.1. The distribution of the location of end users remains the same as was presented in Section 3.2.1. For downstream traffic, we assume that the location of the content requested by an end user is independent of the location of the end user. We also assume that the distribution of the location of the content requested by an end user, namely the distribution of the source S, is identical to the distribution of end users. We further assume that the content provider uses hot potato routing. The routing of downstream traffic is thus identical to that considered in Section 3.2.2. As a result, the distances that the ISP carries downstream traffic from a content provider across the ISP's network remain the same as was presented in Section 3.3.

However, whereas in the ISP-ISP case there was both downstream and upstream traffic, we assume that in the ISP-CP case the volume of upstream traffic is negligible. As a result, the ISP's costs are those discussed in Section 3.3.3, but only for downstream traffic. Equivalently, we can think of this ISP-CP case as being equivalent to an ISP-ISP case with hot potato routing and a traffic ratio of infinity. It follows that the ISP's total cost in this ISP-CP case is the same as the ISP's downstream cost in the ISP-ISP case. In the analytical model, this downstream cost was given by (4.1)-(4.2), and in the numerical model, this downstream cost was given by (4.6).

The effect of the number of interconnection points (N) on the ISP's downstream cost using the analytical model is thus illustrated in figure 4.1. There is little, if any, decrease in the ISP's downstream cost as the number of interconnection points increases. The equivalent effect using the more accurate numerical model is illustrated as the downstream curve in Figure 4.3. Here, the cost is minimized when $N = 1$.

We conclude an ISP has little incentive to peer at multiple IXPs with a content provider that does not replicate content and that uses hot potato routing. This is not surprising, since as we discussed at the end of Section 4.2, it is not rational for an ISP to agree to settlement-free peering with another ISP when the traffic ratio of downstream to upstream traffic is high.

6.2 ISP Backbone Cost Under Full Content Replication

We next consider a content provider that hosts a content server at each IXP at which it agrees to peer with an ISP, that replicates all of its content on each of these servers, and that transmits all of its traffic locally.

The ISP network topology remains the same as was presented in Section 3.1. The distribution of the location of end users remains the same as was presented in Section 3.2.1. However, the location of the content is no longer the same as in previous sections. We now assume that the location of the content requested by an end user is the content server located at the IXP closest to the end user at which the content provider and the ISP agree to peer. Routing is now irrelevant, since the content is entering the ISP's network directly from the content server. The distances that the ISP carries downstream traffic from a content provider across the ISP's network are the same as the distances in the ISP-ISP case that an ISP carries downstream traffic when using cold potato routing, which were given in Section 3.3.2. We again assume that the volume of upstream traffic is negligible. Equivalently, we can think of this ISP-CP case as being equivalent to an ISP-ISP case with cold potato routing and a traffic ratio of infinity.

As a result, the ISP's cost in this ISP-CP case using the analytical model is:

$$C^{ISP}_{ana,(ISP-CP,N,x^d=1)} = c^b V_{down} \left(ED^{b,cold}_{1,down} + \frac{c^m}{c^b} ED^m_1 \right) \tag{6.1}$$

Because the content provider provides all content to the ISP at the IXP nearest to the end user, $ED^{b,cold}_{1,down} = 0$. Substituting the expression we previously found for ED^m_1 in (3.15), we obtain:

$$\begin{aligned} &C^{ISP}_{ana,(ISP-CP,N,x^d=1)} = c^m V_{down} \frac{abN}{LW} \\ &\sum_{m=1}^{\frac{W}{b}} \sum_{n=1}^{\frac{L}{aN}} \sqrt{\left(\frac{(2n-1)a - L/N}{2}\right)^2 + \left(\frac{(2m-1)b - W}{2}\right)^2} \end{aligned} \tag{6.2}$$

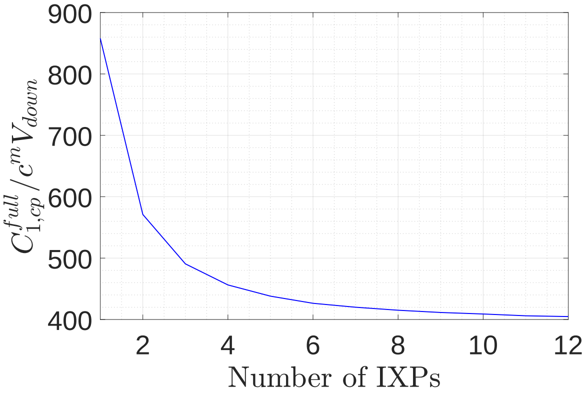
Similarly, using the numerical model, the ISP's cost in this ISP-CP case is:

$$C^{ISP}_{num,(ISP-CP,N,x^d=1)} = c^b V_{down} ED^{b,cold}_{2,down} \tag{6.3}$$

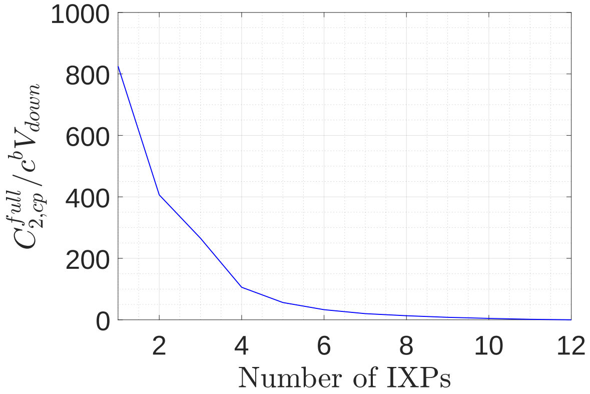
Substituting the expression we previously found for $ED^{b,cold}_{2,down}$ in (3.21), we obtain:

$$\begin{aligned} C^{ISP}_{num,(ISP-CP,N,x^d=1)} = &c^b V_{down} \\ &\sum_{g' \in I^M_2} D^b_2(g \mid g' \in R^N_2(g), g') P(IXP^u_2 = g') \end{aligned} \tag{6.4}$$

The effect of the number of interconnection points (N) on the ISP's downstream cost using both models is illustrated in figure 6.1. The cost decreases as the number of IXPs increases. Note that the ISP has this incentive to increase the number of IXPs at which the two parties



(a) Analytical Model



(b) Numerical Model

Figure 6.1: Costs under complete replication

peer *despite* the fact that the traffic ratio is infinity, unlike in the ISP-ISP case. However, there is less than a 2% difference in the cost between $N = 9$ and $N = 12$ in both models, so this indicates there may be little value in requiring interconnection at more than 9 IXPs.

Using the analytical model, we can compare the cost in the ISP-ISP case (illustrated in figure 4.2) to the cost in this ISP-CP case (illustrated in figure 6.1(a)). In the ISP-ISP case, we found that there is little value in requiring interconnection at more than 8 IXPs. In this ISP-CP case, we found that there is little value in requiring interconnection at more than 9 IXPs. The numerical model shows a similar but more pronounced pattern. Comparing the cost in the ISP-ISP case (illustrated in figure 4.3) to the cost in this ISP-CP case (illustrated in figure 6.1(b)), we find that there is little value in requiring interconnection at more than

6 IXPs in the ISP-ISP case, but there is a significant incremental value in the ISP-CP case to increasing the number of IXPs to at least 9.

The number of interconnection points at which the cost curve flattens is higher in the ISP-CP case than in the ISP-ISP case. In the ISP-CP case, the cost is entirely incurred by carrying downstream traffic, which is localized. In the ISP-ISP case, there are cost components for both downstream and upstream traffic. The upstream cost using hot potato routing is the same as the downstream cost in the ISP-CP case, which is similarly decreasing in N. However, the downstream cost using hot potato routing in the ISP-ISP case is increasing with N, which causes the total cost to flatten out at lower values of N.

This comparison indicates that it is likely rational for an ISP to agree to settlement-free peering with a content provider that replicates its content at all agreed peering points and delivers all traffic locally, as long as it agrees to interconnect at a minimum of 9 IXPs. We would thus expect large ISPs to have *different* settlement-free peering requirements for such content providers than for ISPs. First, we would expect the minimum number of interconnection points to be higher for content providers than ISPs. Second, we would certainly expect there to be *no* traffic ratio requirements for content providers. Third, we expect there to be some type of traffic localization requirement. We turn to this last requirement in the next subsection.

6.3 ISP Backbone Cost Under Partial Content Replication

Finally, we consider a content provider that hosts a content server at each IXP at which it agrees to peer with an ISP, but that replicates only a portion of this content.

The ISP network topology remains the same as was presented in Section 3.1, and the distribution of the location of end users remains the same as was presented in Section 3.2.1. However, the location of the content is no longer the same as in previous sections. We assume that, within each access network, a proportion x^d of requests is served by the content server located at the IXP closest to the end user at which the content provider and the ISP agree to peer. We also assume that, within each access network, the remaining proportion $1 - x^d$ of requests is served by a content server that is independent of the location of the end user, and that the distribution of the location of this content server is identical to the distribution of end users. We further assume that the content provider uses hot potato routing for non-locally delivered content.

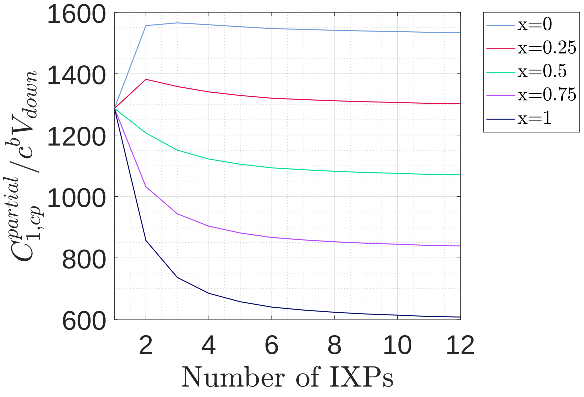
For the analytical model, the ISP's cost in this ISP-CP case is:

$$\begin{aligned} C^{ISP}_{ana,(ISP-CP,N,x^d)} &= x^d C^{ISP}_{ana,(ISP-CP,N,x^d=1)} + (1-x^d) C^{ISP}_{ana,(ISP-CP,N,x^d=0)} = \\ & c^b V_{down}\left(x^d ED^{b,cold}_{1,down} + (1-x^d) ED^{b,hot}_{ana,down} + \frac{c^m}{c^b} ED^m_1 \right) \end{aligned} \tag{6.5}$$

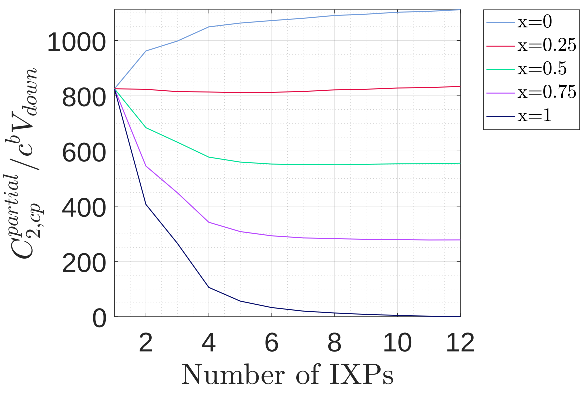
where $ED^{b,cold}_{1,down}$, $ED^{b,hot}_{ana,down}$ and ED^m_1 are given in (4.4), (3.12), and (3.15) respectively.

Figure 6.2(a) shows the effect of the number of interconnection points (N) on the ISP's downstream cost, for various values of the proportion x^d, when $c^m/c^b = 1.5$. When $x^d < 0.3$, too little of the downstream traffic from the content provider to the ISP is delivered locally. The cost of the content delivered using hot potato routing dominates the ISP's downstream cost, and thus it is rational for the ISP to not agree to settlement-free peering. However, when $x^d > 0.3$, the cost of the locally-delivered content dominates the ISP's downstream cost, and thus the ISP benefits from increasing the number of IXPs at which the two parties agree to peer.

THEOREM 6.1. *The traffic-sensitive backbone cost of the ISP when peering with the content*



(a) Analytical ($c^m/c^b = 1.5$)



(b) Numerical Model

Figure 6.2: Costs under partial replication

provider is:

$$C^{ISP}_{num,(ISP-CP,N,x^d)} = c^b V_{down}\Big[x^d ED^{b,cold}_{num,down}(N) + (1-x^d)ED^{b,hot}_{num,down}(N)\Big] \tag{6.6}$$

The proof can be found in the Appendix I. The cost of delivering downstream video traffic is the sum of the costs of delivering localized and non-localized video traffic. The first term, $c^b V_v x^d ED^{b,cold}_{num,down}(N)$, is the ISP's backbone cost for localized video traffic, which accounts for the ISP's transport of a proportion x^d of the video traffic from the IXP nearest to the end user among the IXPs at which they agree to peer. The second term, $c^b V_v(1 - x^d)ED^{b,hot}_{num,down}(N)$, is the ISP's backbone cost for non-localized video traffic, which accounts for the ISP's transport of a proportion $1 - x^d$ of the video traffic from any IXP where they have agreed to peer.

The effect of the number of interconnection points at which they agree to peer (N) on the ISP's downstream cost using the numerical model is illustrated in figure 6.2(b), for various values of the proportion x^d. The pattern is similar to the analytical model. When $x^d < 0.3$, too little of the downstream traffic from the content provider to the ISP is delivered locally, and as before the cost to the ISP increases as the number of IXP increases. However, when $x^d > 0.3$, as before the ISP benefits from increasing the number of IXPs at which the two parties agree to peer.

We conclude that it is likely rational for an ISP to agree to settlement-free peering with a content provider that provides partial replication and delivers that portion locally. We expect that the ISP may require a specified minimum amount of traffic to be delivered locally. We expect the ISP to require interconnection at a specified minimum number of interconnection points, although the number may depend on the amount of traffic delivered locally. However, we certainly expect there to be *no* traffic ratio requirements.

6.4 Cost-Based Peering Fee

We must first address the question of how to define *cost-based* in the context of direct peering between a content provider and an ISP. Should we define *cost-based* as the peering fee that equalizes the net costs of the content provider and the ISP, similar to our analysis above for peering between two ISPs or peering between a transit provider and an ISP? Or should we define *cost-based* as the peering fee that results in the same ISP net costs for transporting the video traffic as in the case in which the video traffic is transported across a transit provider's network?

We believe that the appropriate definition of *cost-based* is the latter one. If we were to attempt to equalize the net costs of the content provider and the ISP, we would have to account for the cost to the content provider of building its CDN. However, as we argued above in the case in which a transit provider deploys a CDN, the decision between building a CDN versus transporting video traffic across the backbone should be made on the basis of the cost of servers versus the transmission cost, not also on the peering fee. Direct peering between a content provider and an ISP is similar. Again, the cost-based peering fee should be determined solely by ensuring that the ISP's net costs are unaffected by the content provider's decision.

Thus, we define the cost-based peering fee between a content provider and an ISP as the fee that results in the same ISP net costs for transporting the video traffic as in the case where the video traffic enters the ISP's network indirectly through a transit provider. Note, however, that this cost-based peering fee is different than that between a transit provider and an ISP for the three reasons discussed above.

Theorem 6.2. *The cost-based peering fee between the content provider and the ISP is:*

$$\begin{aligned} P^{CP,ISP} &= c^b V_v \Big[\Big(0.5 - x^d\Big) ED^{b,hot}_{num,down}(M) \\ &\quad + \Big(1 - x^d\Big)\Big(ED^{b,hot}_{num,down}(N) - ED^{b,hot}_{num,down}(M)\Big) \\ &\quad + x^d \Big(ED^{b,cold}_{num,down}(N) - ED^{b,cold}_{num,down}(M)\Big)\Big] \end{aligned} \tag{6.7}$$

The proof can be found in the Appendix J.

The first term, $c^b V_v (0.5 - x^d) ED^{b,hot}_{num,down}(M)$, represents the effect of video traffic localization on the cost-based peering fee. The second term, $c^b V_v (1 - x^d)(ED^{b,hot}_{num,down}(N) - ED^{b,hot}_{num,down}(M)) + x^d (ED^{b,cold}_{num,down}(N) - ED^{b,cold}_{num,down}(M))$, represents the effect of the number of IXPs at which they agree to peer on the cost-based peering fee.

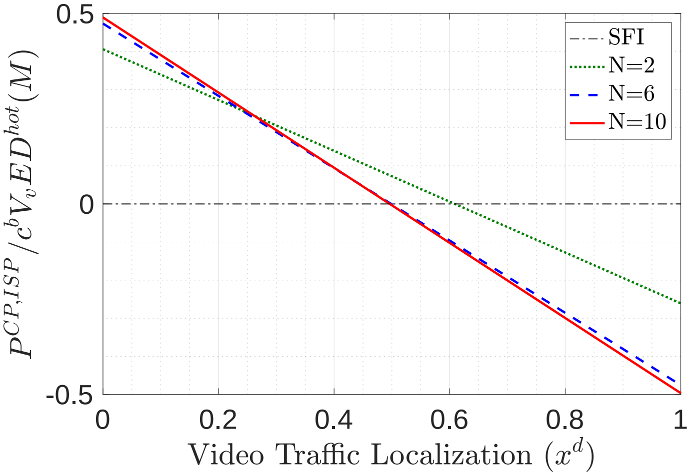


Figure 6.3: Cost-based Peering Fee Between a Content Provider and an ISP

Figure 6.3 illustrates the cost-based peering fee between the content provider and the ISP as a function of video traffic localization and the number of IXPs at which they agree to peer. At low amounts of localization, the cost-based peering fee is positive. However, as the content provider sends traffic with more localization, the cost-based peering fee decreases and at some point becomes negative (meaning that the ISP should pay the content provider).

The cost-based peering fee also varies with the number of IXPs at which they agree to peer. When localization is very low, interconnecting at more IXPs is not beneficial to the ISP, because the ISP needs to carry the video traffic over longer distances in its backbone network since the peering IXP moves farther from the IXP nearest to the end user. Therefore, the cost-based peering fee increases slightly with N at very low amounts of localization. However, for moderate to high localization, interconnecting at more IXPs is beneficial to the ISP, because the ISP's backbone cost decreases since the peering IXP moves closer to the IXP nearest to the end user. Therefore, the cost-based peering fee decreases with N at moderate to high amounts of localization.

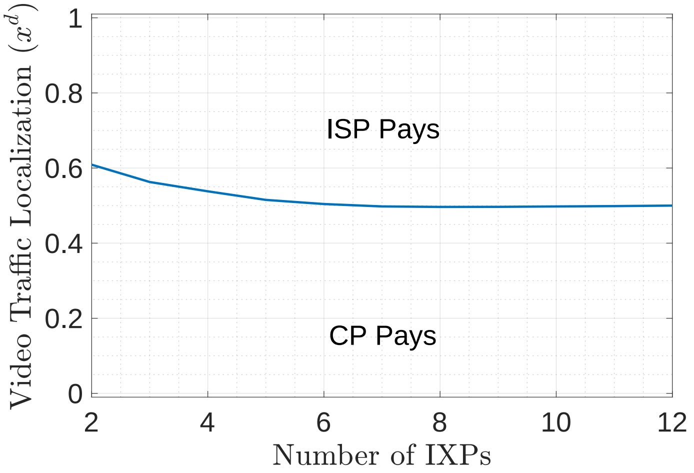


Figure 6.4: Settlement-free Direct Peering Curve

6.5 Settlement-Free Peering

Finally, we wish to determine under what elements of peering policies (namely, the number of interconnection points and video traffic localization) the content provider should be eligible for settlement-free peering. By setting the cost-based peering fee to zero ($P^{CP,ISP} = 0$) in Theorem 6.2, we can determine the number of IXPs and localization required for settlement-free peering:

Theorem 6.3. *The percentage of video traffic localization between a content provider and an ISP required for a cost-based peering fee of zero is:*

$$x^d = \frac{ED^{b,hot}_{num,down}(N) - 0.5ED^{b,hot}_{num,down}(M)}{ED^{b,hot}_{num,down}(N) - ED^{b,cold}_{num,down}(N)} \tag{6.8}$$

Figure 6.4 illustrates the settlement-free peering curve for direct interconnection between a content provider and an ISP, as a function of the amount of video traffic localization and the number of IXPs at which they peer. Recall from Figure 5.4, which illustrated the settlement-free peering curve for interconnection between a transit provider and an ISP, that 50% localization is sufficient for settlement-free peering when the non-video traffic ratio

$r^{nv} = 1$, but that different amounts of localization may be required for other non-video traffic ratios and it may depend on the amount of video traffic. For direct interconnection between a content provider and an ISP, the traffic ratio is now irrelevant because the net cost to the ISP of transporting the video traffic is solely a function of localization.[1] Indeed, if the content provider and the ISP agree to peer at all $N = 12$ locations, then 50% localization is sufficient to justify settlement-free peering.

As the number of interconnection points decreases from $N = 12$, the content provider should send an increasing proportion of video traffic locally in order to be eligible for settlement-free peering. However, when $8 \leq N \leq 12$, there is little variation in ISP's backbone cost and thus little change in the amount of localization required for settlement-free peering.

6.6 Evaluation of Arguments

Recall that large ISPs often argue that they should apply the same settlement-free peering requirements to peering ISPs, peering transit providers, and peering content providers. However, whereas when two ISPs peer we have shown that the cost-based peering fee is a function of the traffic ratio, when a content provider and an ISP peer we have shown that the cost-based peering fee is a function of the number of interconnection points and of localization. Hence, different settlement-free peering should apply to these two situations.

Also, recall that large ISPs often argue that they should be compensated by large content providers regardless of the amount of video content localization. Again we disagree. Our results show that it is rational for an ISP to agree to settlement-free peering with a content provider that delivers a sufficient amount of video traffic locally.

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[1] The required localization is solely dependent on the location of the interconnection points and the distribution of video traffic among the population. The other parameters of our model do not affect the settlement-free peering curve.

Similarly, recall that large content providers sometimes argue that they should be entitled to settlement-free peering solely because the ISP's customers have already paid the ISP to transport the traffic the content providers are sending. We believe this argument is too simplistic. We have shown that the cost-based peering fee should include consideration of the ISP's backbone transportation cost and thus of the number of interconnection points and of localization. A more nuanced argument by large content providers is that they should be eligible for settlement-free peering if they bring the content close to customers. We have shown that localization should indeed play a key role in determining eligibility for settlement-free peering.

Chapter 7

Peering Between A Content Provider And A Profit-Maximizing ISP: An Analytical Two-sided Market Model

In this sections, we explore the dynamics of peering arrangements between large content providers and a profit-maximizing ISP. We offer both analytical and numerical insights into the two-sided market. We propose a model of user subscription to broadband service tiers and to subscription video on demand (SVOD) services. We consider a monopoly ISP that offers different tiers. We aggregate all SVOD providers that directly interconnect with the ISP. Consumers differ in the utilities they place on broadband service tiers and on SVOD service, and each customer chooses the service which maximizes his/her surplus. We derive the demand of each broadband service tier and of SVOD services, the associated consumer surplus, the associated ISP profit, and aggregated SVOD providers' profit.

We consider a monopoly ISP that offers basic and premium tiers differentiated by bandwidth and price. To focus on the effect of peering fees, we propose a two-sided model in which a monopoly ISP maximizes its profit by choosing broadband prices as well as a peering price. An ISP earns revenue by increasing its peering price, but this will also trigger a decrease in the demand for the ISP's premium tier. An ISP also earns revenue by increasing its premium tier price, but this will also trigger a decrease in demand for SVOD services and thus in the revenue from paid peering. We derive numerical model parameters based on public data about broadband and SVOD services prices and subscription.

We prove that an ISP maximizes its profit by choosing prices that satisfy a generalization of the well-known Lerner rule, which specifies how these prices are related to a matrix of elasticities and cross-elasticities of demand. We then consider the effect of paid peering on broadband prices as well as ISP profit. ISPs assert that paid peering revenue is offset by lower broadband prices, and that ISP profits remain unchanged. Content providers assert that peering prices do not result in lower broadband prices, but simply increase ISP profits. Using our model, we find that the basic tier price is almost unaffected by peering fees, but that the premium tier price is lower when an ISP chooses the paid peering price to maximize profit than when settlement-free peering is used. Also, we find that positive peering prices result in increased ISP profit and in decreased SVOD services profit.

Finally, we consider the impact of paid peering on consumer surplus. ISPs assert that paid peering fees increase aggregate consumer surplus because they eliminate an inherent subsidy of consumers with high video streaming use by consumers without such use. However, content providers assert that paid peering fees decrease consumer surplus because they are passed onto consumers through higher SVOD services prices without a corresponding reduction in broadband prices. To address this question, we consider the peering price to be an independent variable set by a regulator with the goal of maximizing consumer surplus. We show that consumer surplus is a uni-modal function of the peering price, and that the peering price that maximizes consumer surplus is substantially less than the peering price that maximizes ISP profit and less than the incremental ISP cost per video streaming subscriber.

We show that the peering price depends critically on this cost, and that at different costs it can be negative, zero, or positive. Then we formulate an optimization problem in which a regulator maximizes consumer surplus by choosing not only the peering price but also the broadband prices and the aggregate SVOD services price. We show that the resulting peering price is the ISP cost per SVOD services subscriber plus the desired rate of return.

7.1 A Model of User Subscription to Broadband and to Video Streaming

Before we can analyze the effect of paid peering on broadband prices, we need a model of user subscription to broadband service tiers and to video streaming.

7.1.1 Service offerings

ISPs offer multiple tiers of broadband services, differentiated principally by download speed. ISPs typically market these broadband service tiers by recommending specific tiers to consumers who engage in specific types of online activities. For example, Comcast recommends a lower service tier to consumers who principally use their Internet connection for email and web browsing, but a higher service tier to consumers who use the Internet for video streaming. Much of the debate over paid peering concerns consumers who stream large volumes of video. Thus, we construct here a model that includes two broadband service tiers: a basic tier with a download speed intended for email, web browsing, and a limited amount of video streaming; and a premium tier (at a higher price) with a download speed intended for a substantial amount of video streaming. Although most often ISPs offer more than two tiers, the majority of customers subscribe to a subset of two tiers, and this two-tier model is sufficient to separately evaluate the effect of paid peering prices on consumers who utilize video streaming and on consumers who don't.

Specifically, we model a single monopoly ISP that offers a basic tier at a monthly price P^b and a premium tier at a monthly price P^b+P^p. We consider N consumers, each of whom may subscribe to the basic tier, the premium tier, or neither. We denote user i's utility per month from subscription to the basic tier by b_i, and user i's utility per month from subscription to the premium tier by $b_i + p_i$. We presume that a consumer who gains significant utility from video streaming subscribes to the premium tier.

To analyze the effect of paid peering prices on broadband prices, we focus on the aggregate of all video streaming providers that directly interconnect with the ISP and that may pay (or be paid) a fee for peering with the ISP. We model the aggregate of all plans offered by these video streaming providers, but to keep the model tractable we consider a single price of P^v per month for the aggregate. We denote user i's utility per month from subscription to video streaming providers by v_i. Consumer i's utility from all other content is included in $b_i + p_i$.

Consumers differ in the utilities they place on broadband service tiers and on video streaming. We assume that the number of consumers N is large, and we denote the joint probability density function of their utilities by $f_{B,P,V}(b,p,v)$.

7.1.2 Demand functions

Each consumer thus has four choices

$$X_i \triangleq \begin{cases} n, & \text{do not subscribe} \\ b, & \text{subscribe to the basic tier} \\ p, & \text{subscribe to the premium tier but not to a video streaming provider} \\ v, & \text{subscribe to the premium tier and to a video streaming provider.} \end{cases} \tag{7.1}$$

Consumer i's consumer surplus, defined as utility minus cost, under each choice is thus

$$CS_i(X_i; b_i, p_i, v_i) = \begin{cases} 0, & X_i = n \\ b_i - P^b, & X_i = b \\ b_i + p_i - P^b - P^p, & X_i = p \\ b_i + p_i + v_i - P^b - P^p - P^v, & X_i = v. \end{cases} \tag{7.2}$$

Each consumer is assumed to maximize consumer surplus. Thus, consumer i adopts the choice

$$X_i^*(b_i, p_i, v_i) \triangleq \arg\max_{X_i} CS_i(X_i; b_i, p_i, v_i), \tag{7.3}$$

and earns a corresponding consumer surplus $CS_i^* \triangleq CS_i(X_i^*)$.

Each of the N consumers makes an individual choice per (7.3). The consumers who choose to subscribe to the basic tier are those whose utility b_i from subscription to the basic tier exceeds its monthly price P^b, whose incremental utility p_i from subscription to the premium tier without subscribing to a video streaming provider falls below the incremental monthly price P^p, and whose incremental utility $p_i + v_i$ from subscription to the premium tier and to video streaming falls below the corresponding incremental monthly price $P^p + P^v$. Thus, the demand[1] for the basic tier is given by

$$N^b(P^b, P^p, P^v) = N \int_{-\infty}^{P^p} \int_{-\infty}^{P^p+P^v-p} \int_{P^b}^{\infty} f_{B,P,V}(b, p, v)\, db\, dv\, dp. \tag{7.4}$$

Similarly, the consumers who choose to subscribe to the premium tier but not to video streaming are those whose utility $b_i + p_i$ from subscription to the premium tier exceeds its

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[1] Since we model a finite number N of consumers whose utilities are given by a joint probability density function, this equation, and other similar equations below, give the *average demand.* However, for simplicity of presentation, we use the term *demand.*

monthly price $P^b + P^p$, whose incremental utility p_i from subscription to the premium tier without subscribing to video streaming exceeds the incremental monthly price P^p, and whose incremental utility v_i from subscription to video falls below the incremental monthly price P^v. Thus, the number of consumers who subscribe to the premium tier but who do not subscribe to video streaming is given by

$$N^p(P^b, P^p, P^v) = N \int_{-\infty}^{P^v} \int_{P^p}^{\infty} \int_{P^b+P^p-p}^{\infty} f_{B,P,V}(b, p, v)\ db\ dp\ dv. \tag{7.5}$$

Finally, the consumers who choose to subscribe to both the premium tier and video streaming are those whose utility $b_i + p_i + v_i$ from subscription to both services exceeds the combined cost $P^b + P^p + P^v$, whose incremental utility $p_i + v_i$ from subscription to only the basic tier exceeds the corresponding incremental price $P^p + P^v$, and whose incremental utility v_i from subscription to video streaming falls exceeds the incremental monthly price P^v. Thus, the demand for video streaming is given by

$$N^v(P^b, P^p, P^v) = N \int_{P^v}^{\infty} \int_{P^p+P^v-v}^{\infty} \int_{P^b+P^p+P^v-p-v}^{\infty} f_{B,P,V}(b, p, v)\ db\ dp\ dv. \tag{7.6}$$

The demand for the premium tier is $N^p + N^v$, the sum of the demands for the premium tier without and with a subscription to the streaming video provider.

7.1.3 Consumer surplus

The aggregate consumer surplus will be an important quantity to consider in our deliberations below. It can be easily determined for each set of consumers using the number of subscribers in each set (7.4-7.6) and the surplus of each consumer (7.2). Given a set of prices, the aggregate consumer surplus of subscribers to the basic tier is

$$CS^b(P^b, P^p, P^v) = N \int_{-\infty}^{P^p} \int_{-\infty}^{P^p+P^v-p} \int_{P^b}^{\infty} (b - P^b) f_{B,P,V}(b, p, v) \; db \; dv \; dp. \tag{7.7}$$

Similarly, the aggregate consumer surplus of consumers who subscribe to the premium tier but not to video streaming is

$$CS^p(P^b, P^p, P^v) = N \int_{-\infty}^{P^v} \int_{P^p}^{\infty} \int_{P^b+P^p-p}^{\infty} (b + p - P^b - P^p) f_{B,P,V}(b, p, v) \; db \; dp \; dv, \tag{7.8}$$

and the aggregate consumer surplus of consumers who subscribe to both the premium tier and video steaming is

$$CS^v(P^b, P^p, P^v) = N \int_{P^v}^{\infty} \int_{P^p+P^v-v}^{\infty} \int_{P^b+P^p+P^v-p-v}^{\infty} (b+p+v-P^b-P^p-P^v) f_{B,P,V}(b, p, v) \; db \; dp \; dv. \tag{7.9}$$

The aggregate consumer surplus over all consumers is defined as

$$CS(P^b, P^p, P^v) \triangleq CS^b(P^b, P^p, P^v) + CS^p(P^b, P^p, P^v) + CS^v(P^b, P^p, P^v) \tag{7.10}$$

7.1.4 Profits

We assume that the ISP incurs a monthly marginal cost C^b per basic tier subscriber. The ISP marginal profit per basic tier subscriber is thus $P^b - C^b$. We assume that the ISP incurs a monthly marginal cost $C^b + C^p$ per premium tier subscriber who does not also subscribe to video streaming. The ISP marginal profit per such broadband service tier subscriber is thus $P^b + P^p - C^b - C^p$. We also assume that the capacity is fixed in our model.

The marginal cost to an ISP associated with video streaming is at the core of the debate over paid peering, and thus we must be careful in its formulation. Here, we have assumed that only premium tier subscribers engage in a substantial amount of video streaming, consistent with ISP marketing of their service tiers. We have further divided premium tier subscribers according to whether they also subscribe to video streaming services that have direct interconnection with the ISP.

For generality, we thus associate an ISP monthly marginal cost $C^b + C^P + C^d$ per video streaming subscriber, where the d denotes direct interconnection. The incremental ISP cost C^d per video streaming subscriber may be negative, zero, or positive. It is critical to note that this incremental cost is not that of the interconnection point itself between the ISP and each video streaming provider, as the cost of the interconnection point itself is negligible. However, there are several variables that may affect the incremental ISP cost per video streaming subscriber. First, video streaming subscribers receive substantially more traffic per month than premium tier subscribers who don't subscribe to video streaming. Second, when a content provider switches from indirect interconnection through a transit provider to an ISP to direct interconnection with the ISP, the location of the interconnection point may change. This change in the location of the interconnection point may result in either shorter or longer paths on the ISP's network from the interconnection point to the subscriber, and thus either a lower or higher incremental ISP cost per video streaming subscriber.

We also consider a peering price of P^d per video streaming subscriber for direct interconnection between the ISP and video streaming providers. This price may be positive if the ISP charges video streaming providers for direct interconnection, negative if the video streaming providers charge the ISP for direct interconnection, or zero if the peering is settlement-free.

The ISP marginal profit per video streaming subscriber is $P^b + P^p + P^d - C^b - C^p - C^d$.

The total ISP profit (excluding fixed costs)[2] is thus

$$\pi^{ISP}(P^b, P^p, P^d, P^v) = (P^b - C^b)N^b + (P^b + P^p - C^b - C^p)N^p + (P^b + P^p + P^d - C^b - C^p - C^d)N^v. \tag{7.11}$$

We assume that the video streaming providers incur a monthly marginal cost C^v per subscriber. The aggregate video streaming provider marginal profit per subscriber is thus $P^v - C^v - P^d$, and their total profit (excluding fixed costs)[3] is

$$\pi^{VSP}(P^b, P^p, P^d, P^v) = (P^v - C^v - P^d)N^v. \tag{7.12}$$

7.2 A Two-Sided Model for ISP Profit Maximization

The previous section presented a model for consumer demand for broadband and video streaming, resulting in the demand functions (7.4-7.6), the corresponding aggregate consumer surplus (7.7-7.9), and the corresponding ISP and video streaming provider profits (7.11-7.12). In this section, we formulate a two-sided model of how the prices are determined.

7.2.1 Analytical model

There are a number of options for modeling how the broadband service tier prices (P^b and P^p), the video streaming price (P^v), and the peering price (P^d) are determined.

Throughout the section, we presume that the ISP has no significant competition for broadband service at acceptable speeds within the footprint of its service territory. Thus, we

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[2] Throughout the section, ISP profit excludes fixed costs.

[3] Throughout the section, aggregate video streaming profit excludes fixed costs.

assume that the ISP determines its broadband service tier prices (P^b and P^p) to maximize its profit.

A key question, critical to this analysis, is how the peering price (P^d) is determined. Once a subscriber chooses an ISP, the ISP has a monopoly on the transport of traffic within the ISP's access network that the customer resides in. In contrast, there may be a competitive market for the transport of Internet traffic across core networks. In this section, we assume that the location of direct interconnection between the ISP and each video streaming provider is close enough to the consumers so that all of the transport from the interconnection point to the consumers falls within the ISP's access network. Correspondingly, we assume that the ISP has the market power to determine the peering price (P^d) and that it sets this price to maximize its profit.

The ISP thus chooses the broadband service tier prices (P^b and P^p) and the peering price (P^d) to maximize its profit, namely

$$(P^b_{ISP}, P^p_{ISP}, P^d_{ISP}) = \arg \max_{(P^b, P^v, P^d)} \pi^{ISP}(P^b, P^p, P^d, P^v) \tag{7.13}$$

In contrast, we assume that the market determines the aggregate video streaming price, excluding paid peering fees, when there is no regulation of prices. We denote the aggregate video streaming price, excluding paid peering fees, by P^v_0. We presume that an ISP charging peering prices would likely charge them to both directly interconnected content providers and directly interconnected transit providers. We further presume that transit providers would pass peering prices through to their customers. As a consequence, we foresee that peering prices would be paid by all large video service providers selling to the ISP's customers. An open question is whether the video streaming providers can pass through any peering price (P^d) to their customers by adding it to their video streaming prices. We denote the pass-through rate of the peering fee by $0 < \alpha \leq 1$:

$$P^v(P^d) = P_0^v + \alpha P^d \tag{7.14}$$

Equations (7.13-7.14) set up a two-sided model in which the ISP earns revenue from both its customers and video service providers (if $P^d > 0$). The combination of the two equations captures the inter-dependencies between the ISP, the video services providers, and the consumers. The ISP-determined peering price (P^d), along with the pass-through rate (α), leads to an aggregate video streaming price (P^v). The ISP-determined broadband service tier prices (P^b and P^p), along with the aggregate video streaming price (P^v), lead to demands for each broadband service tier (N^b and $N^p + N^v$) and for video streaming services (N^v). These demands in turn affect how the ISP sets each of the prices.

Since the aggregate video service price (P^v) is solely determined by (7.14), we can represent the ISP's profit as a function of three variables rather than four:

$$(P_{ISP}^b, P_{ISP}^p, P_{ISP}^d) = \arg \max_{(P^b, P^v, P^d)} \pi^{ISP}(P^b, P^p, P^d, P_0^v + \alpha P^d) \tag{7.15}$$

7.2.2 Numerical parameters

This two-sided model is somewhat amenable to closed-form analysis. However, we find it useful to also examine the model under a set of realistically chosen parameters. We set out those parameters in this subsection.

The joint probability density function of user utilities for the basic tier, the premium tier, and video streaming is represented by $f_{B,P,V}(b, p, v)$. For numerical evaluation, we assume that each utility is independent and has a Normal distribution: $B \sim \mathcal{N}(\mu_b, \sigma_b^2), P \sim \mathcal{N}(\mu_p, \sigma_p^2), V \sim \mathcal{N}(\mu_v, \sigma_v^2)$. We need to determine numerical values for the means and variances.

The ISP incurs a monthly marginal cost of C^b per subscriber, a monthly marginal cost of C^p per premium tier subscriber, and an incremental ISP cost C^d per video streaming subscriber. We need to determine numerical values for these three costs.

Unfortunately, direct information about user utilities and ISP costs is scarce. Instead, we choose numerical values for user utilities and ISP costs indirectly using available information about demand and prices in the United States.

There are several sets of publicly available statistics about broadband prices and subscriptions [79, 80]. While the set of statistics differ, they show that roughly 75% of households in the United States subscribe to fixed broadband service. Hence, we wish to choose numerical values for user utilities and ISP costs so that, at the ISP profit-maximizing prices, $(N^b + N^p + N^v)/N = 0.75$. For each ISP, the statistics show that subscribers predominately choose among two service tiers, which we map to the basic and premium tiers modeled above, with roughly 2/3 of subscribers choosing the premium tier. Hence, we wish to choose numerical values for user utilities and ISP costs so that, at the ISP profit-maximizing prices, $N^b/N = (0.75)(1/3) = 0.25$ and $(N^p + N^v)/N = (0.75)(2/3) = 0.50$. Moreover, the statistics also reveal that the price of the lower of the two popular tiers is roughly \$50 per month, and the price of higher of the two popular tiers is roughly \$70 per month. Hence, we wish to choose numerical values for user utilities and ISP costs so that the ISP profit-maximizing prices are $P^b = \$50.00$ and $P^p = \$20.00$.

According to [81], Americans subscribe to an average of three paid video streaming providers. There are also several sets of publicly available statistics about video streaming prices and subscriptions [82, 83]. While the set of statistics differ, they show that roughly 50% of households in the United States that subscribe to fixed broadband service also subscribe to at least two video streaming services. Hence, we wish to choose numerical values for user utilities and ISP costs so that, at the ISP profit-maximizing prices, $N^v/N = (0.75)(0.5) = 0.375$.

There is even less information about the variance of user utilities, or correspondingly about the elasticity of demand. We choose $\sigma_b = \mu_b/4$, $\sigma_p = \mu_p/4$, and $\sigma_v = \mu_v/4$, which results in reasonably wide distributions.[4]

From these statistics, we can generate targets for the ISP profit-maximizing broadband prices P^b and P^p, and for the demands N^b, N^p, and N^v at these prices. We cannot, however, use these statistics to generate a target for the ISP profit-maximizing peering fee P^d, since information about these fees is scarce. Instead, we estimate the incremental ISP cost C^d per video streaming subscriber. There are some statistics about the monthly usage of various sets of broadband subscribers. None of these are detailed enough to accurately estimate the monthly usage from video streaming. We use a very rough estimate of 400 GB per month of aggregate usage per subscriber, including 300 GB per month of aggregate video streaming per video streaming subscriber. We need to translate this estimate of usage to an estimate of ISP cost. Unfortunately, we know very little about ISP network costs. At a price of \$70/month for 400 GB, the price is \$0.175/GB. However, the marginal cost is much lower than this price, due to high fixed costs. Here we use \$0.01/GB, but we acknowledge this could be far off from the real value. Combining these two estimates, we obtain a target of $C^d = \$3.00$ per month per video subscriber. That said, later in this section, we will consider a wide range of values of C^d.

This now gives us six target values (P^b, P^p, N^b, N^p, N^v, and C^d) to determine the six desired parameters (μ_b, μ_p, μ_v, C^b, C^p, and P^d). We can use the three equations for demand (7.4-7.6) and the ISP profit maximization equation (7.15) to determine these six desired parameters. The result is: $\mu_b \approx \$56.12$, $\mu_p \approx \$18.91$, $\mu_v \approx \$27.67$, $C^b \approx \$16.50$, $C^p \approx \$19.00$, and $P^d \approx \$4.59$. In addition, we assume the aggregate video streaming price $P_0^v = \$21.58$, based

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[4] The results below are not very sensitive to these choices.

on the aggregate price of the three most popular video streaming services.[5] In addition, although we consider any pass-through rate of the paid peering fee ($0 < \alpha \leq 1$), in the numerical results below we use $\alpha = 1$.

We use these parameters in the remainder of the section except as noted. In section 7.6, we will discuss the sensitivity of the numerical results to these numerical parameters.

7.2.3 Profit-maximizing prices

We now turn to the determination of the prices that an ISP chooses in order to maximize profit.

A common measure of a firm's market power is the Lerner index. When a firm has a single product, the Lerner index is defined by $L \triangleq \frac{P-MC}{P}$, where P is the price of the product and MC is the firm's marginal cost. When a firm is a monopoly, $L > 0$ and the Lerner Rule shows that the firm maximizes its profit when $-\varepsilon L = 1$, where ε is the price elasticity of demand.

In our model, however, there is more than one product. When a firm offers two products, say product x and product y, there are two price elasticities of demand. Denote the price elasticity of demand for product x by $\varepsilon_{N^x,P^x} \triangleq \frac{\partial N^x}{\partial P^x}\frac{P^x}{N^x}$, and denote the price elasticity of demand for product y by $\varepsilon_{N^y,P^y} \triangleq \frac{\partial N^y}{\partial P^y}\frac{P^y}{N^y}$, where N^j and P^j are the demand and price of product j respectively. There are also two cross elasticities of demand. Denote the cross-price elasticity of demand for product y with respect to the price of product x by $\varepsilon_{N^y,P^x} \triangleq \frac{\partial N^y}{\partial P^x}\frac{P^x}{N^y}$, and the cross-price elasticity of demand for product x with respect to the price of product y by $\varepsilon_{N^x,P^y} \triangleq \frac{\partial N^x}{\partial P^y}\frac{P^y}{N^x}$.

There are two Lerner indices: $L^x \triangleq \frac{P^x-C^x}{P^x}$ and $L^y \triangleq \frac{P^y-C^y}{P^y}$, where C^x and C^y are the

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[5] The sum of the advertised prices of the lowest price plans for Netflix, Hulu/Disney+, and HBO Max is \$26.17[46, 84–86]. From this sum, we subtract the peering fee $P^d = \$4.59$.

marginal costs for products x and y respectively. Whereas for a single product a firm maximizes its profit when $-\varepsilon L = 1$, when a firm offers two products there is a generalization of the Lerner Rule that the firm maximizes its profit when

$$-\begin{bmatrix} \varepsilon_{N^x,P^x} & \varepsilon_{N^x,P^y} \\ \varepsilon_{N^y,P^x} & \varepsilon_{N^y,P^y} \end{bmatrix} \begin{bmatrix} L^x \\ L^y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix} \tag{7.16}$$

However, our model differs in two aspects from the general theory of profit maximization with multiple products. First, the two broadband tiers are related to each other, and thus we find it awkward to consider the prices of the two broadband tiers as independently chosen using (7.16). Second, we must also consider the ISP's choice of the peering price (P^d), even though it is not by itself the price of a third product. We consider these two challenges in turn.

First, we consider the issue that the two broadband tiers are related to each other. Rather than the ISP independently choosing the prices of each tier, it is more transparent to consider the ISP as choosing the price of the basic tier (P^b) and the incremental price (P^p) to upgrade from the basic tier to the premium tier. This is simply a change of basis. Consider product x to be the basic tier, and product y to be the premium tier without a video streaming subscription. It follows that:

$$\begin{bmatrix} P^x \\ P^y \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} P^b \\ P^p \end{bmatrix} \tag{7.17}$$

Denote the price elasticity of demand for the basic tier by $\varepsilon_{N^b,P^b} \triangleq \frac{\partial N^b}{\partial P^b}\frac{P^b}{N^b}$, and denote the price elasticity of demand for the premium tier without a video streaming subscription by $\varepsilon_{N^p,P^p} \triangleq \frac{\partial N^p}{\partial P^p}\frac{P^p}{N^p}$. Denote the cross price elasticity of demand for the premium tier without a video streaming subscription with respect to the price of the basic tier by $\varepsilon_{N^p,P^b} \triangleq \frac{\partial N^p}{\partial P^b}\frac{P^b}{N^p}$, and the cross price elasticity of demand for the basic tier with respect to the incremental price of the premium tier by $\varepsilon_{N^b,P^p} \triangleq \frac{\partial N^b}{\partial P^p}\frac{P^p}{N^b}$.

There are two Lerner indices: $L^b \triangleq \frac{P^b - C^b}{P^b}$ and $L^p \triangleq \frac{P^p - C^p}{P^p}$. If we ignore the third choice (subscription to both the premium tier and video streaming), we can derive a similar Lerner Rule for the new basis[6]:

$$-\begin{bmatrix} \varepsilon_{N^b,P^b} & \varepsilon_{N^b,P^p} \\ \varepsilon_{N^p,P^b} & \varepsilon_{N^p,P^p} \end{bmatrix} \begin{bmatrix} L^b \\ L^p \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix} \tag{7.18}$$

Second, we consider the issue of the ISP's choice of the peering price (P^d). It is not straightforward to incorporate this price into the Lerner Rule, since the peering price does not by itself represent the price of a third product.

We examine the situation from the perspective of the ISP. According to (7.15), the ISP is choosing three prices: (P^b, P^p, P^d). These three prices affect the demand for three products: b, p, and v. The profit-maximizing relationship between the prices P^b and P^p and their corresponding elasticities would be given by (7.18) in the absence of video streaming and a peering price.

Even though the peering price P^d does not directly represent a third product, the ISP perceives the peering price as determining the number of customers N^v who subscribe to both the premium tier and video streaming. Thus, mimicking the general approach for multiple products, we can define a price elasticity of demand for joint premium tier and video streaming subscription with respect to the paid peering price, denoted by $\varepsilon_{N^v,P^d} \triangleq \frac{\partial N^v}{\partial P^d}\frac{P^d}{N^v}$. We also define the other cross price elasticities of demand: $\varepsilon_{N^b,P^d} \triangleq \frac{\partial N^b}{\partial P^d}\frac{P^d}{N^b}$, $\varepsilon_{N^p,P^d} \triangleq \frac{\partial N^p}{\partial P^d}\frac{P^d}{N^p}$,

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[6] The proof can be found in Appendix O.

$\varepsilon_{N^v,P^b} \triangleq \frac{\partial N^v}{\partial P^b}\frac{P^b}{N^v}$, and $\varepsilon_{N^v,P^p} \triangleq \frac{\partial N^v}{\partial P^p}\frac{P^p}{N^v}$. There is now a third Lerner index: $L^d \triangleq \frac{P^d - C^d}{P^d}$.

We assume that the joint probability density function $f_{B,P,V}(b,p,v)$ is continuous and bounded. We can now derive a Lerner Rule for the ISP profit maximization problem:

Theorem 7.1. *If there is a 100% pass-through rate of the paid peering fee, the profit-maximizing prices* $(P^b_{ISP}, P^p_{ISP}, P^d_{ISP})$ *in (7.15) satisfy:*

$$-\begin{bmatrix} \varepsilon_{N^b,P^b} & \varepsilon_{N^b,P^p} & \varepsilon_{N^b,P^d} \\ \varepsilon_{N^p,P^b} & \varepsilon_{N^p,P^p} & \varepsilon_{N^p,P^d} \\ \varepsilon_{N^v,P^b} & \varepsilon_{N^v,P^p} & \varepsilon_{N^v,P^d} \end{bmatrix} \begin{bmatrix} L^b \\ L^p \\ L^d \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \tag{7.19}$$

The proof can be found in K.

7.2.4 Elasticities of demand

Stakeholders disagree about the relationship between peering fees and demand. In this subsection, we first give the signs of elasticities in Theorem 7.1 and then investigate their numerical values using our numerical parameters.

Theorem 7.2. *At the profit-maximizing prices* $(P^b_{ISP}, P^p_{ISP}, P^d_{ISP})$*: The self price elasticities of demand are negative:* $\varepsilon_{N^b,P^b} < 0$, $\varepsilon_{N^p,P^p} < 0$, *and* $\varepsilon_{N^v,P^d} < 0$. *The cross price elasticity of demand for the basic tier with respect to the incremental price* P^p *is positive:* $\varepsilon_{N^b,P^p} > 0$. *The cross price elasticity of demand for the premium tier without video streaming with respect to the price of the basic tier is negative:* $\varepsilon_{N^p,P^b} < 0$. *The cross price elasticity of demand for either tier without video streaming with respect to the peering price is positive:* $\varepsilon_{N^b,P^d} > 0$, *and* $\varepsilon_{N^p,P^d} > 0$. *The cross price elasticity of demand for video streaming with respect to the price of either tier is negative:* $\varepsilon_{N^v,P^b} < 0$, *and* $\varepsilon_{N^v,P^p} < 0$.

The proof can be found in L.

Using the numerical parameters given in Section 7.2.2, the price elasticities of demand are:

$$\begin{bmatrix} \varepsilon_{N^b,P^b} & \varepsilon_{N^b,P^p} & \varepsilon_{N^b,P^d} \\ \varepsilon_{N^p,P^b} & \varepsilon_{N^p,P^p} & \varepsilon_{N^p,P^d} \\ \varepsilon_{N^v,P^b} & \varepsilon_{N^v,P^p} & \varepsilon_{N^v,P^d} \end{bmatrix} = \begin{bmatrix} -1.93 & 3.39 & 0.36 \\ -1.50 & -4.20 & 0.63 \\ -1.09 & -1.50 & -0.55 \end{bmatrix} \tag{7.20}$$

The signs of these elasticities match those given in Theorem 2. Note, however, that these price elasticities of demand are those at the ISP profit-maximizing prices and that they will vary substantially at different prices.

There are several academic papers that have estimated the price elasticity of demand for broadband. However, none of these papers consider multiple tiers of service, and hence all estimate only the price elasticity of demand for broadband service over all tiers. The price elasticity of demand for broadband estimated in these papers ranges from −0.18 to −3.76 [87–92].

Recall that the demand for broadband service is $N^b + N^p + N^v$. Using the numerical parameters given in Section 7.2.2, the price elasticities of demand for broadband service with respect to the basic tier price P^b and with respect to the incremental premium tier price P^p, respectively, are:

$$\begin{aligned} \varepsilon_{(N^b+N^p+N^v),P^b} &= \frac{N^b \varepsilon_{N^b,P^b} + N^p \varepsilon_{N^p,P^b} + N^v \varepsilon_{N^v,P^b}}{N^b + N^p + N^v} = -1.44 \\ \varepsilon_{(N^b+N^p+N^v),P^p} &= \frac{N^b \varepsilon_{N^b,P^p} + N^p \varepsilon_{N^p,P^p} + N^v \varepsilon_{N^v,P^p}}{N^b + N^p + N^v} = -0.32 \end{aligned} \tag{7.21}$$

The range of price elasticities of demand for broadband estimated in the literature thus encapsulates our estimates for the price elasticities of demand for broadband service with respect to the basic tier price P^b and with respect to the incremental premium tier price P^p.

The self price elasticities of demand are negative, meaning that neither broadband service nor video streaming is a Giffen good. The three demand functions in (7.4-7.6), along with the relationship in (7.14) between the peering price and the aggregate video streaming price, can be used to determine the impact of changes in the three prices P^b, P^p, and P^d, and thus of the signs of the cross-price elasticities of demand.

If the ISP increases the price of the premium tier by increasing the incremental price P^p (but leaves P^b and P^d unchanged), then some subscribers to the premium tier downgrade to the basic tier, resulting in a decrease in the demand $N^p + N^v$ for the premium tier and an increase in the demand N^b for the basic tier. The increase in the price of the premium tier also decreases the demand N^v for video streaming. Thus $\varepsilon_{N^b,P^p} > 0$ and $\varepsilon_{N^v,P^p} < 0$. Using our numerical parameters given in section 7.2.2, $\varepsilon_{N^b,P^p} = 3.39$, $\varepsilon_{N^p,P^p} = -4.20$, and $\varepsilon_{N^v,P^p} = -1.50$.

If the ISP increases the prices of both broadband service tiers by increasing P^b (but leaves P^p and P^d unchanged), then demand for both broadband tiers decrease. The increase in the price of the premium tier also decreases the demand N^v for video streaming. Thus $\varepsilon_{N^p,P^b} < 0$ and $\varepsilon_{N^v,P^b} < 0$. Using our numerical parameters, $\varepsilon_{N^b,P^b} = -1.93$, $\varepsilon_{N^p,P^b} = -1.50$ and $\varepsilon_{N^v,P^b} = -1.09$.

In contrast, if the ISP increases the price P^b for the basic tier but keeps unchanged the price $P^b + P^p$ for the premium tier (and leaves P^d unchanged), then some subscribers to the basic tier upgrade to the premium tier, and some stop subscribing to broadband Internet access altogether, resulting in a decrease in the demand N^b for the basic tier and an increase in the demand $N^p + N^v$ for the premium tier. The increase in demand for the premium tier also increases the demand N^v.

If the ISP increases the peering price P^d (but leaves P^b and P^p unchanged), then this causes the video streaming providers to increase the aggregate price P^v. The effect is that some subscribers to the video streaming service discontinue their video streaming subscription but retain enough incremental utility to remain subscribers to the premium tier. Other subscribers to video streaming discontinue their video streaming subscriptions and, having lost the associated utility, now downgrade to the basic tier. As a result, the demand N^v for the video streaming service decreases, the demand N^p for the premium tier without video streaming increases, and the demand N^b for the basic tier increases. Thus, $\varepsilon_{N^b,P^d} > 0$ and $\varepsilon_{N^p,P^d} > 0$. Using our numerical parameters, $\varepsilon_{N^b,P^d} = 0.36$, $\varepsilon_{N^p,P^d} = 0.63$, and $\varepsilon_{N^v,P^d} = -0.55$. In addition, the demand $N^p + N^v$ for the premium tier decreases.

Theorem 1 shows that the price for consumers is proportional to the marginal cost of providing services to each tier. However, the marginal rate of return may be dramatically different for the different tiers. Using our numerical parameters, the marginal rate of return on the basic tier is very large, with $(P^b - C^b)/C^b \approx 200\%$. The marginal rate of return on the incremental price from the basic tier to the premium tier may be small; using our numerical parameters, we have $(P^p - C^p)/C^p \approx 5\%$. There may also be a substantial marginal rate of return on the ISP's chosen peering fee; using our numerical parameters $(P^d - C^d)/C^d \approx 50\%$. However, these marginal rates of return do not consider fixed costs, which are likely to dominate the total cost of providing broadband service, since our model has no need to consider fixed costs.

7.3 The Effect of Paid Peering on Prices

We now consider the effect of paid peering on broadband prices. ISPs assert that paid peering revenue is offset by lower broadband prices, and that ISP profits remain unchanged. Content providers assert that peering prices do not result in lower broadband prices, but simply increase ISP profits. The goal is this section is to evaluate these assertions.

With an understanding of how the ISP sets the prices $(P^b_{ISP}, P^p_{ISP}, P^d_{ISP})$, we can now evaluate the impact of the peering price P^d upon the broadband prices P^b and P^p.

As we did in the previous section, we assume that the video streaming price P^v is set by (7.14). However, whereas in (7.15) the ISP sets the peering price P^d to maximize profit, in this section we make the peering price P^d an independent variable so that we can judge its impact on other prices.

Given a specified peering price P^d_{reg}, the ISP is assumed to choose the tier prices P^b and P^p so as to maximize profit, namely

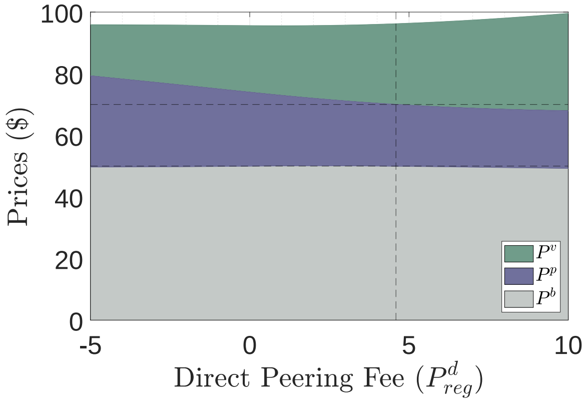
$$(P^b_{reg}, P^p_{reg}) = \arg \max_{(P^b, P^p)} \pi^{ISP}(P^b, P^p, P^d_{reg}, P^v_0 + \alpha P^d_{reg}). \tag{7.22}$$

The ISP chosen prices (P^b_{reg}, P^p_{reg}) are a function of the independently set price P^d_{reg}. The video streaming price P^v is also a function of P^d_{reg}.

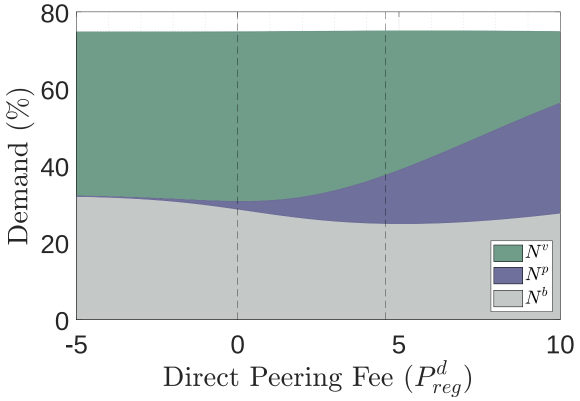
Figure 7.1(a) shows the prices of both broadband tiers and the aggregate video streaming price as a function of the independently chosen peering fee P^d_{reg}.

We initially compare prices and profits in the case in which the ISP chooses the peering price to maximize profit ($P^d = \$4.59$) to the case in which settlement-free peering is used (i.e., $P^d = \$0$). We start at the profit-maximizing peering price $P^d = \$4.59$ and consider a small decrease. If the ISP did not change the prices for the broadband tiers (which it will), then a small decrease in the peering price would result in a small decrease in demand for the basic tier (because $\varepsilon_{N^b,P^d} = 0.36$), a small decrease in demand for the premium tier without video streaming (because $\varepsilon_{N^p,P^d} = 0.63$), and a small increase in demand for the premium tier with video streaming (because $\varepsilon_{N^v,P^d} = -0.55$).

However, the ISP now has the motivation to modify the broadband tier prices. The decrease in the peering price results in a decrease in the aggregate price of video streaming. As



(a) Effect of Peering Fee on Broadband Prices and the Aggregate Video Streaming Price



(b) Effect of Peering Fee on Demand (Percentage to Total)

Figure 7.1: Effects of Peering Fee

a consequence, the ISP will recoup most of the decreased peering price by increasing the incremental price for the premium tier P^p. It does not, however, change the basic tier price P^b by much at all, since increasing the premium tier price results in some users downgrading to the basic tier, which more than offsets those who would otherwise upgrade from the basic tier to the premium tier to take advantage of lower video streaming prices. The signs of these trade-offs remain the same in the entire range from $P^d = \$4.59$ to $P^d = \$0$.

Figure 7.1(b) shows the corresponding demands for each broadband tier and for video streaming. Again, we start at the profit-maximizing peering price $P^d = \$4.59$ and consider a small decrease. The ISP's increase in the premium tier price drives some consumers who subscribe

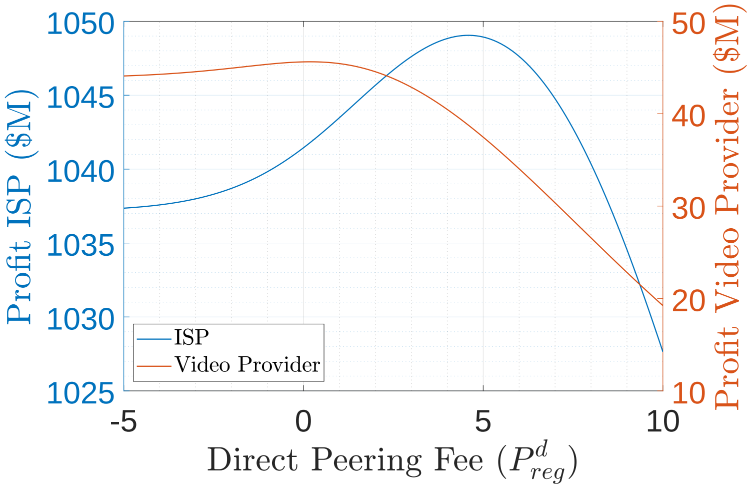


Figure 7.2: Effect of Peering Fee on Profit of ISP and Video Streaming Provider

to the premium tier but not to video streaming to downgrade to the basic tier. However, the total price for the premium tier and video streaming, $P^b + P^p + P^v$, decreases, and thus some consumers who subscribe to the premium tier but not to video streaming now choose to start subscribing to video streaming.

Figure 7.2 shows the corresponding ISP profit and aggregate video streaming provider profit. Again, we start at the profit-maximizing peering price $P^d = \$4.59$ and consider a small decrease. The ISP's profit from the video streaming subscribers increases because the demand N^v increases and the price per subscriber $P^b + P^p$ increases. The ISP's profit from premium tier subscribers without video streaming decreases, because the demand N^p decreases more than the price $P^b + P^p$ increases. Finally, the ISP's profit from basic tier subscribers increases, because the demand N^b increases while the price P^b remains virtually unchanged.

We can now evaluate the stakeholder claims about the effect of paid peering on broadband prices and ISP profits. Recall that ISPs assert that paid peering revenue is offset by lower broadband prices, whereas content providers assert that peering prices do not result in lower broadband prices. We find that the basic tier price P^b is almost the same in the case in which the ISP chooses the peering price to maximize profit ($P^d = \$4.59$) as in the case in which settlement-free peering is used ($P^d = \$0$). We also find that the premium tier price $P^b + P^p$ decreases by \$3.98 (from \$73.98 to \$70.00) if we change from settlement-free peering ($P^d = \$0$) to paid peering ($P^d = \$4.59$), but the aggregate video streaming price increases by \$4.60 (from \$21.59 to \$26.19). Thus, to the extent that ISPs assert that paid peering reduces the price of the basic tier, we disagree. Paid peering should be expected to reduce the price of the premium tier, but this reduction in broadband price is more than offset by an increase in video streaming prices.

Recall that ISPs assert that their profits are unaffected by peering fees, whereas content providers assert that peering fees increase ISP profits. We find that the ISP profit increases by 0.8% if we change from settlement-free peering ($P^d = \$0$) to paid peering ($P^d = \$4.59$). However, the larger effect is on aggregate video streaming profit, which decreases by 18%.

7.4 The Effect of Paid Peering on Aggregate Consumer Surplus

In the previous section, we analyzed the effect of paid peering on broadband prices. In this section, we turn to the impact of paid peering on consumer surplus. ISPs assert that paid peering fees increase aggregate consumer surplus because they eliminate an inherent subsidy of consumers with high video streaming use by consumers without such use. Content providers assert that paid peering fees decrease aggregate consumer surplus because they are passed onto consumers through higher video streaming prices without a corresponding reduction in broadband prices.

A portion of these assertions was addressed in the previous section. We now know that when an ISP sets peering prices so as to maximize profit, it sets those prices to be positive. Compared to settlement-free peering, positive peering prices result in reduced premium tier prices. Directly connected video streaming providers increase their prices to compensate. However, the ISP only passes onto its customers a portion of the paid peering revenue.

However, this leaves unanswered the question of the impact on aggregate consumer surplus. It also leaves unanswered the question of what value of peering price maximizes aggregate consumer surplus. We attempt to answer those questions now.

We consider the peering price P^d to be an independent variable set by a regulator. The aggregate consumer surplus $CS(P^b_{CS_{reg}}, P^p_{CS_{reg}}, P^v)$ is a function of P^d. The regulator is presumed to set the peering price P^d so that it maximizes aggregate consumer surplus:

$$\begin{aligned}(P^b_{CS_{reg}}, P^p_{CS_{reg}}) &= \arg\max\nolimits_{(P^b,P^p)} \pi^{ISP}(P^b, P^p, P^d_{CS_{reg}}, P^v_0 + \alpha P^d_{CS_{reg}}) \\ P^d_{CS_{reg}} &= \arg\max\nolimits_{P^d} CS(P^b_{CS_{reg}}(P^d), P^p_{CS_{reg}}(P^d), P^d, P^v_0 + \alpha P^d).\end{aligned} \tag{7.23}$$

Equation (7.23) determines the resulting aggregate consumer surplus maximizing value of the peering price P^d, as well as the resulting broadband prices P^b and P^p and video streaming price P^v.

Another optimization metric commonly used is aggregate social welfare, which we define here as

$$W(P^b, P^p, P^d, P^v) \triangleq CS(P^b, P^p, P^v) + \pi^{ISP}(P^b, P^p, P^d, P^v) + \pi^{VSP}(P^b, P^p, P^d, P^v). \tag{7.24}$$

Note that whereas the ISP profit maximization problem (7.15) considers only ISP profit, and the aggregate consumer surplus maximization problem (7.23) considers only consumer surplus, social welfare includes both ISP profit and consumer surplus, as well as aggregate video streaming provider profit.

Although we believe that a regulator should attempt to maximize consumer surplus not

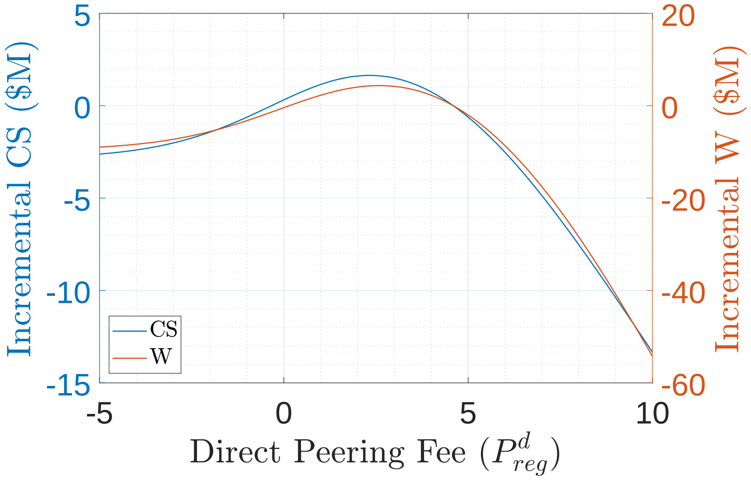


Figure 7.3: Effect of Peering Fee on Incremental Consumer Surplus and Incremental Social Welfare

aggregate social welfare, the social welfare maximization problem is:

$$\begin{aligned}(P^b_{W_{reg}}, P^p_{W_{reg}}) &= \arg\max_{(P^b,P^b)} \pi^{ISP}(P^b, P^p, P^d_{W_{reg}}, P^v_0 + \alpha P^d_{W_{reg}}) \\ P^d_{W_{reg}} &= \arg\max_{P^d} W(P^b_{W_{reg}}, P^p_{W_{reg}}, P^d, P^v_0 + \alpha P^d).\end{aligned} \tag{7.25}$$

However, the optimization problem is no longer analytically tractable. Thus, we will turn back to our numerical evaluation. Figure 7.3 shows the incremental consumer surplus as a function of the regulator chosen peering price P^d. The incremental consumer surplus is defined as the difference between the aggregate consumer surplus at the regulator chosen peering price P^d and at the peering price that maximizes ISP profit (P^d_{ISP}).

Aggregate consumer surplus is a uni-modal function of the peering price. We find that the peering price that maximizes consumer surplus is $P^d_{CS_{reg}} = \$2.34$. This is substantially less than the peering price that maximizes ISP profit (P^d_{ISP}=\$4.59). At peering prices lower than \$2.34, aggregate consumer surplus decreases principally because the premium tier price is too high, and this decreases the surplus of premium tier subscribers. At peering prices higher than \$2.34, aggregate consumer surplus decreases principally because the price of video streaming is too high, and this decreases the surplus of video streaming subscribers.

To understand why, we need to revisit the impact of the peering price on broadband tier prices and demand, and how these changes in price and demand affect aggregate consumer surplus. We compare prices and demands in the case in which the ISP chooses the peering price to maximize profit ($P^d_{ISP} = \$4.59$) to the case in which the regulator chooses the peering price to maximize aggregate consumer surplus ($P^d_{CS_{reg}} = \$2.34$).

As we discussed in the previous section, a reduction in the peering price below that which maximizes ISP profit results in lower aggregate video streaming prices and increased premium tier prices. However, the amount of the increase in the premium tier price is less than the amount of the decrease in the aggregate video streaming price. Thus, the price of the premium tier with video streaming ($P^b + P^p + P^v$) decreases. These changes in prices cause some premium tier subscribers without video streaming to downgrade to the basic tier, and some to start subscribing to video streaming.

These changes in prices and demand affect aggregate consumer surplus. Figure 7.4 shows the aggregate consumer surplus of all subscribers to the basic tier, to the premium tier without video streaming, and to the premium tier with video streaming. A reduction in the peering price below that which maximizes ISP profit results in increased demand for the basic tier, but with basic tier prices virtually unchanged. The result is that the aggregate consumer surplus of basic tier subscribers increases. A reduction in the peering price also results in increased premium tier prices and decreased demand for the premium tier without video streaming. The result is that the aggregate consumer surplus of premium tier subscribers without video streaming decreases. Finally, a reduction in the peering price results in decreased prices of the premium tier with video streaming and increased demand. The result is that the aggregate consumer surplus of premium tier subscribers with video streaming increases. The aggregate consumer surplus is the sum of these three. As the peering price decreases from the price that maximizes ISP profit (P^d_{ISP}=\$4.59) to the price that maximizes consumer surplus ($P^d_{CS_{reg}} = \$2.34$), the increase in the aggregate consumer surplus of basic

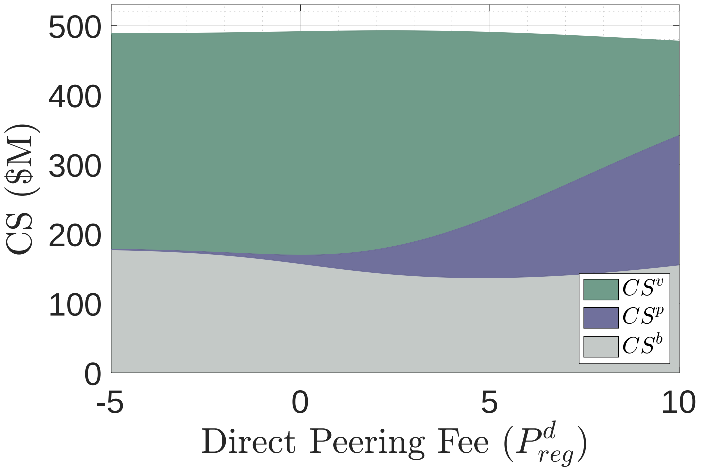


Figure 7.4: Effect of Peering Fee on Consumer Surplus with Different Services

tier subscribers and premium tier subscribers with video streaming dominates the decrease in the aggregate consumer surplus of premium tier subscribers without video streaming. However, at peering prices below the price that maximizes consumer surplus ($P^d_{CS_{reg}} = \$2.34$), the opposite is true.

Finally, we consider the difference if a regulator would choose the peering price that maximizes aggregate social welfare (7.25) instead of maximizing aggregate consumer surplus (7.23). Figure 7.3 shows the incremental social welfare as a function of the regulator chosen peering price P^d. The incremental social welfare is defined as the difference between the aggregate social welfare at the regulator chosen peering price P^d and at the peering price that maximizes ISP profit (P^d_{ISP}).

Recall that the aggregate social welfare is the sum of ISP profit, aggregate video streaming provider profit, and aggregate consumer surplus. As discussed in the previous section, the ISP profit decreases as the peering price decreases below \$4.59, because the ISP's increase in the premium tier price is less than the decrease in the peering price. However, the aggregate video streaming provider profit increases, because demand for video streaming increases and the profit per video streaming subscriber remains constant. Finally, as discussed above, the aggregate consumer surplus increases until the peering price goes below \$2.34.

Aggregate social welfare is a uni-modal function of the peering price. We find that the peering price that maximizes social welfare is $P^d_{W_{reg}} = \$2.61$. This is substantially less than the peering price that maximizes ISP profit ($P^d_{ISP} = \$4.59$), but higher than the peering price that maximizes aggregate consumer surplus ($P^d_{CS_{reg}} = \$2.34$). As the peering price decreases from the price that maximizes ISP profit ($P^d_{ISP} = \$4.59$) to the price that maximizes social welfare ($P^d_{W_{reg}} = \$2.61$), the sum of the increase in the aggregate video streaming provider profit and increase in the aggregate consumer surplus dominates the decrease in ISP profit. At peering prices below \$2.61 but above \$2.34, the opposite is true.

We can now evaluate the stakeholder claims about the effect of paid peering on consumer surplus. Recall that ISPs assert that paid peering fees increase aggregate consumer surplus whereas content providers assert that they decrease aggregate consumer surplus. The peering price that maximizes aggregate consumer surplus is below the price that maximizes ISP profit. Using our numerical parameters, we found that the peering price that maximizes aggregate consumer surplus is $P^d_{CS_{reg}} = \$2.34$, whereas if unregulated the ISP would choose $P^d_{ISP} = \$4.59$. Furthermore, we found that aggregate consumer surplus is \$1.65M higher at the peering price that maximizes aggregate consumer surplus than at the peering price that maximizes ISP profit. However, we also found that when the incremental ISP cost per video streaming subscriber is $C^d = \$3.00$, aggregate consumer surplus is \$1.33M higher at the peering price that maximizes aggregate consumer surplus than at settlement-free peering ($P^d = \$0$). Thus, neither settlement-free peering nor paid peering with an ISP-determined price maximizes consumer surplus.

7.5 The Effect of the Incremental ISP Cost C^d Per Video Streaming Subscriber

The peering price that maximizes aggregate consumer surplus depends critically on the incremental ISP cost C^d per video streaming subscriber. Without knowledge of this cost, we cannot say whether the peering price that maximizes aggregate consumer surplus is negative, zero, or positive. In this section, we consider how the incremental ISP cost C^d per video streaming subscriber affects the results. For each value of C^d, we determine the numerical parameters (μ_b, μ_p, μ_v, C^b, C^p, and P^d) using the method discussed in Section 7.2.2. This analysis is thus a study of the impact of the unknown value of C^d, given fixed values for the observed known parameters.

Figure 7.5 shows the peering prices that maximize ISP profit, aggregate consumer surplus, and aggregate social welfare as a function of the incremental ISP cost C^d per video streaming subscriber.Thus, not only does C^d direct affect the peering prices, it also indirectly affects all prices and demands. The peering price that maximizes aggregate consumer surplus, $P^d_{CS_{reg}}$, increases nearly linearly, from -\$1.80 to \$2.34 as C^d increases from -\$1.12 to \$3.00. Notably, it is positive when $C^d >$ \$0.68, but negative at lower values of C^d. Recall that the incremental ISP cost C^d per video streaming subscriber depends on both the incremental Internet usage of video streaming subscribers over non-subscribers and the length of the path on the ISP's network. As video content providers interconnect with the ISP closer to consumers, the incremental ISP cost C^d per video streaming subscriber decreases, and may be negative if the interconnection point is close enough to the consumer. In contrast, if the interconnection point is far from the consumer, then the incremental Internet usage may dominate and C^d may be positive.

If a regulator were to set the peering price to maximize social welfare, then $P^d_{W_{reg}}$ similarly

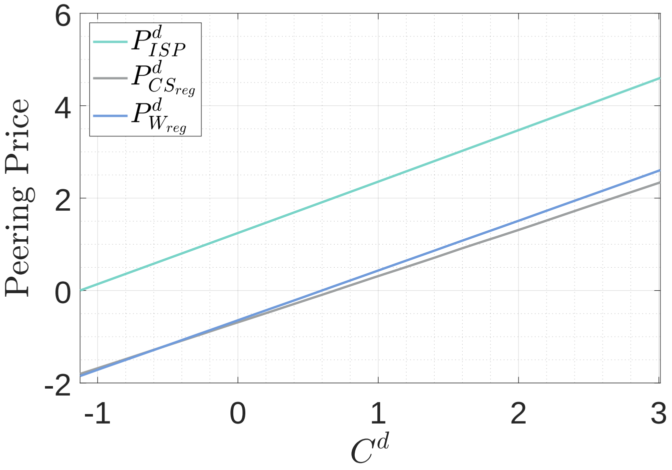


Figure 7.5: Effect of the Incremental ISP Cost Per Video Streaming Subscriber on the Peering Price

increases from -\$1.85 to \$2.61 as C^d increases from -\$1.12 to \$3.00. This closely tracks $P^d_{CS_{reg}}$, with the difference diminishing at lower costs. The peering price that maximizes ISP profit, P^d_{ISP}, also increases nearly linearly with the incremental ISP cost C^d per video streaming subscriber, from \$0.00 to \$4.59 as C^d increases from -\$1.12 to \$3.00. Notably, the incremental ISP profit $P^d_{ISP} - C^d$ per video streaming subscriber remains positive at all values above $C^d = -\$1.12$, and indeed increases with higher values of C^d.

The effect on consumers is qualitatively similar, but different in magnitude. When $C^d =$ \$3.00, premium tier subscribers without video streaming would pay \$70.00 at the ISP chosen peering price (P^d = \$4.59) but \$71.69 if the regulator sets the peering price to maximize consumer surplus (P^d = \$2.34), and premium tier subscribers with video streaming would pay \$96.19 at the ISP chosen peering price but \$95.61 at the regulator chosen peering price. Thus, regulation of the peering price results in premium tier subscribers without video streaming paying \$1.69 more and in premium tier subscribers with video streaming paying \$0.58 less; however the regulated peering price also increases demand for video streaming from 37.5% to 42.6%.

When $C^d = -\$1.12$, premium tier subscribers without video streaming would pay \$70.00 at the ISP chosen peering price but \$71.37 at the regulator chosen peering price, and premium tier subscribers with video streaming would pay \$91.59 at the ISP chosen peering price but \$91.15 at the regulator chosen peering price. Thus, regulation of the peering price results in premium tier subscribers without video streaming paying \$1.37 more and in premium tier subscribers with video streaming paying \$0.44 less; however the regulated peering price also increases demand for video streaming from 37.5% to 42.3%.

Finally, we revisit our evaluation of stakeholder claims about broadband prices, ISP profit, and consumer surplus, under different values of the incremental ISP cost C^d per video streaming subscriber. If $C^d = \$3.00$, we found that paid peering should be expected to reduce the price of the premium tier, but this reduction in broadband price is more than offset by an increase in video streaming prices. At lower values of C^d, paid peering still should be expected to reduce the price of the premium tier, but less so. Similarly, neither the change in ISP profit nor the change in video streaming profit is very sensitive to C^d.

If $C^d = \$3.00$, we found that aggregate consumer surplus is \$1.65M higher at the peering price that maximizes aggregate consumer surplus than at the peering price that maximizes ISP profit, but that aggregate consumer surplus is also \$1.33M higher at the peering price that maximizes aggregate consumer surplus than at settlement-free peering ($P^d = \$0$). Figure 7.6 shows the incremental consumer surplus, which is the difference between the aggregate consumer surplus at ISP-chosen peering price and that at the peering price that maximizes consumer surplus, for various values of C^d. We observe that the incremental consumer surplus is significant at all values of C^d, rising from \$1.02M to \$1.63M as C^d increases from -\$1.12 to \$3.00.

The incremental ISP cost C^d per video streaming subscriber, however, does have a large impact on the optimal peering price. The peering price that maximizes consumer surplus is strongly correlated with C^d. At values of $C^d > \$0.68$, settlement-free peering is too aggressive. and the regulator should limit the peering price to at least \$2.00 less than the

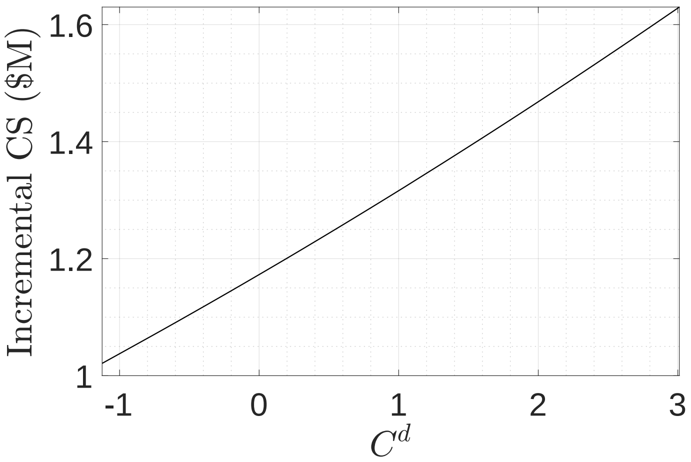


Figure 7.6: Effect of the Incremental ISP Cost Per Video Streaming Subscriber on the Incremental Consumer Surplus

ISP-chosen peering price. At negative values of C^d, settlement-free peering is too timid, and the ISP should pay content providers for paid peering at locations so close to the consumers. At small positive values of C^d ($0 < C^d < \$0.68$), the ISP bears a cost, but the peering price that maximizes consumer surplus is negative; we turn to this issue next.

So far, we found that the peering price that maximizes aggregate consumer surplus ($P^d_{CS_{reg}}$) is less than the incremental network cost C^d for video streaming. This result seems counter-intuitive, since we generally expect that consumer surplus is maximized when prices reflect costs. In order to explain this result, we formulate an optimization problem in which a regulator maximizes aggregate consumer surplus by choosing not only the peering price P^d but also the broadband prices P^b and P^p and the aggregate video streaming price P^v. We are not proposing that a regulator control all of these prices, but it will serve as an informative comparison.

Given a set of prices, the aggregate consumer surplus was given in (7.10). An overly simplistic approach to maximizing aggregate consumer surplus would be to choose the consumer-facing prices:

$$
\begin{aligned}
(P^b_{CS}, P^p_{CS}, P^v_{CS}) = & \arg \max_{(P^b, P^p, P^v)} CS(P^b, P^p, P^v) \\
& \text{s.t.} \\
& P^b_{CS} \geq 0 \\
& P^p_{CS} \geq 0 \\
& P^v_{CS} \geq 0.
\end{aligned} \tag{7.26}
$$

However, we can show that the marginal aggregate consumer surplus with respect to the tier prices and the peering price are all negative:

THEOREM 7.3.

$$
\begin{aligned}
&\frac{\partial CS}{\partial P^b} = -N^b - N^p - N^v < 0 \\
&\frac{\partial CS}{\partial P^p} = -N^p - N^v < 0 \\
&\frac{\partial CS}{\partial P^v} = -N^v < 0.
\end{aligned} \tag{7.27}
$$

The proof can be found in M.

It follows that the solution to (7.26) is at $P^b = P^p = P^v = 0$. It is common to guarantee that a business's rate of return does not fall below a specified minimum. The rate of return for the ISP is

$$
r^{ISP}(P^b, P^p, P^d, P^v) \triangleq \frac{\pi^{ISP}(P^b, P^p, P^d, P^v)}{(C^b)N^b + (C^b + C^p)N^p + (C^b + C^p + C^d)N^v}. \tag{7.28}
$$

The rate of return of the video streaming providers is

$$
r^{VSP}(P^b, P^p, P^d, P^v) \triangleq \frac{\pi^{VSP}(P^b, P^p, P^d, P^v)}{C^v N^v}. \tag{7.29}
$$

Maximization of aggregate consumer surplus, subject to rate of return constraints for both the ISP and the video streaming providers, is:

$$\begin{aligned} (P^b_{CS}, P^p_{CS}, P^d_{CS}, P^v_{CS}) = \arg \max_{(P^b, P^v, P^d, P^v)} & \; CS(P^b, P^p, P^v) \\ \text{s.t.} & \\ r^{ISP}(P^b, P^p, P^d, P^v) & \geq r^{ISP}_{\min} \\ r^{VSP}(P^b, P^p, P^d, P^v) & \geq r^{VSP}_{\min}, \end{aligned} \tag{7.30}$$

where $r^{ISP}_{\min}$ is the specified minimum rate of return for the ISP, and $r^{VSP}_{\min}$ is the specified minimum rate of return for the video streaming providers. Although aggregate consumer surplus is not directly a function of the peering price P^d, the peering price P^d is present in the rate of return constraints.

It follows that the prices that maximize aggregate consumer surplus are those at which the rate of return constraints are binding:

Theorem 7.4. *The prices $(P^b_{CS}, P^p_{CS}, P^d_{CS}, P^v_{CS})$ that maximize aggregate consumer surplus in (7.30) are:*

$$\begin{aligned} P^b_{CS} &= (r^{ISP}_{\min} + 1)C^b \\ P^p_{CS} &= (r^{ISP}_{\min} + 1)C^p \\ P^d_{CS} &= (r^{ISP}_{\min} + 1)C^d \\ P^v_{CS} &= (r^{VSP}_{\min} + 1)(C^v + P^d_{CS}). \end{aligned} \tag{7.31}$$

The proof can be found in N.

The prices that maximize aggregate consumer surplus are thus those that allow the ISP to cover the costs of each tier and the cost of paid peering (if any), plus the specified rate of return.

We wish to compare the solution to this maximization problem to the solution of the ISP profit maximization problem (7.15) and to the solution of the aggregate consumer surplus maximization problem with a regulator-chosen peering price (7.23). For numerical purposes, we set $r_{\min}^{ISP} = r_{\min}^{VSP} = 13.6\%$.[7] The solution to (7.30) is: $P_{CS}^{b} = \$18.74$, $P_{CS}^{p} = \$21.58$, $P_{CS}^{d} = \$3.41$, and $P_{CS}^{v} = \$25.00$.

The peering price that maximizes aggregate consumer surplus under rate of return constraints, $P_{CS}^{d} = \$3.41$, is equal to the incremental network cost $C^{d} = \$3.00$ for video streaming plus the desired minimal rate of return. This is less than the peering price that maximizes ISP profit, $P_{ISP}^{d} = \$4.59$, but greater than the peering price that maximizes aggregate consumer surplus, $P_{CS_{reg}}^{d} = \$2.34$.

If the regulator instead chooses all of the prices, then it will choose all prices equal to cost plus the desired rate of return, according to Theorem 7.4. However, when the regulator can set the peering price, but allows the ISP to set the broadband prices, the regulator chooses a price $P_{CS_{reg}}^{d} = \$2.34 < C^{d} = \$3.00$. The reason for setting the price below cost is that the regulator cannot directly control the broadband prices, P^{b} and $P^{b} + P^{p}$, both of which substantially exceed cost plus the desired rate of return. In the absence of such control, aggregate consumer surplus is maximized by a peering price less than cost.

7.6 Sensitivity

Although the theorems presented here hold for all values of parameters (except that Theorem 1 requires a 100% pass-through rate), the numerical results depend on the numerical values chosen for these parameters. To judge whether the results presented here are robust to the values chosen for these parameters, we repeated all numerical analyses in this dissertation with a wide range of values of the following parameters, each of which was changed one at

---

[7] This rate of return is taken from [93], the 2019 Netflix 10-K report.

a time:

- the ISP profit-maximizing basic tier price (P^b),
- the ISP profit-maximizing incremental premium tier price (P^p),
- the standard deviations of user utilities ($\sigma_b^2, \sigma_p^2, \sigma_v^2$),
- the percentage of the population that subscribes to broadband ($(N^b + N^p + N^v)/N$),
- the percentage of broadband subscribers who subscribe to the basic tier ($N^b/(N^b + N^p + N^v)$),
- the percentage of premium tier subscribers who subscribe to video streaming services ($N^v/(N^p + N^v)$),
- the aggregate video streaming price with settlement-free peering (P_0^v), and
- the pass-through rate (α).

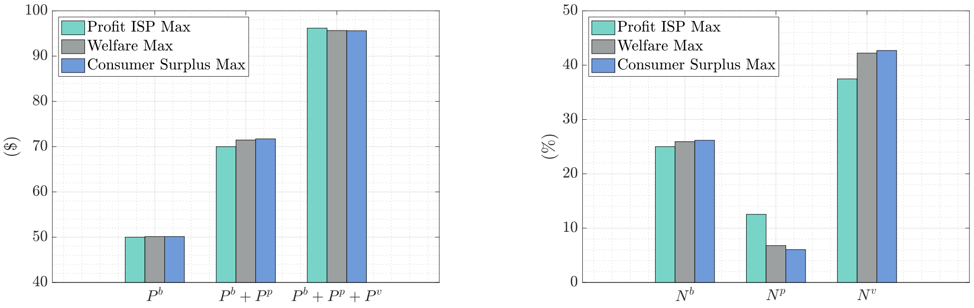
Although the numerical results depend on the numerical values of these parameters, all of the qualitative results presented in this dissertation remain true for all parameter ranges that we analyzed (except for the qualitative result about welfare-maximization, as discussed above). We briefly discuss here the sensitivity of our results to these parameter choices.

The ISP profit-maximizing paid peering fee is relatively insensitive to the ISP profit-maximizing basic tier price (P^b) and to the incremental premium tier price (P^p). However, it is positively correlated with the standard deviations of user utilities; higher standard deviations increase the willingness-to-pay of video streaming subscribers (who have above average utilities), which the ISP can then leverage through higher peering fees.

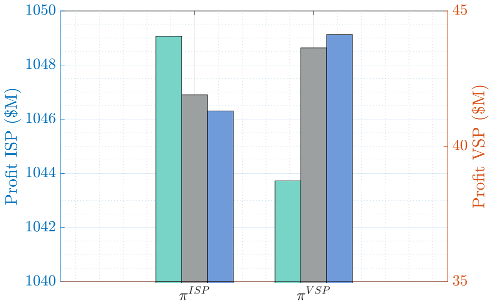
The ISP profit-maximizing paid peering fee is moderately positively correlated with the percentage of the population that subscribes to broadband ($(N^b + N^p + N^v)/N$), because higher broadband demand increases premium tier demand and thus compensates for the decreased demand that would be caused by a higher peering fee. It is relatively moderately negatively correlated with the percentage of broadband subscribers who subscribe to the basic tier ($N^b/(N^b + N^p + N^v)$), because higher relative demand for the basic tier decreases demand for the premium tier, which causes the ISP to decrease the peering fee. The ISP profit-maximizing paid peering fee is strongly positively correlated with the percentage of premium tier subscribers who subscribe to video streaming services ($N^v/(N^p+N^v)$), because the ISP can take advantage of the higher relative demand for video streaming.

The ISP profit-maximizing paid peering fee is moderately positively correlated with the aggregate video streaming price under settlement-free peering (P_0^v), because the ISP can increase its paid peering fee to take advantage of higher streaming providers' revenue.

Finally, the ISP profit-maximizing paid peering fee is strongly inversely correlated with the pass-through rate of paid peering. When the pass-through rate decreases below 100%, the ISP can increase its paid peering fee to take advantage of the lower sensitivity of premium tier subscribers to the paid peering fee. The ISP will also moderately decrease the incremental premium tier price to increase premium tier demand. The ISP's decrease in revenue from premium tier subscribers is more than offset by its increase in revenue from paid peering. The impact upon video streaming providers' profit increases as the pass-through rate decreases. With lower pass-through rates, video streaming providers have less ability to recoup paid peering fees, and the gap between the profit they earn under ISP profit-maximizing paid peering fees and the profit they would earn under paid peering fees that maximize consumer surplus grows.



(a) Prices (b) Demand



(c) Profit

Figure 7.7: Comparison between different policies

7.7 Comparison

We also determined the peering fees that maximize either consumer surplus or social welfare, such as a regulator may set. We compared the effect of an ISP-chosen peering fee with a regulator-chosen peering fee. Figure 7.7 summarizes our results. We find when that a regulator sets the peering price to maximize consumer surplus, it chooses a lower peering price than does the ISP. As a result, video streaming prices drop to reflect the lower video streaming costs. However, the ISP then increases the price of the premium tier, recouping most of its loss from the lower peering price and regaining some of the increased consumer surplus from lower video streaming prices.

Chapter 8

Peering Between A Content Provider And A Profit-Maximizing ISP: A Numerical Two-sided Market Model

In this section, we explore the dynamics of peering arrangements between large content providers and a profit-maximizing ISP. We focus solely on the numerical aspects. Additionally, our model incorporates the consideration of an unlimited add-on fee among the variables that ISPs may charge customers. We propose a model of user subscription to broadband service tiers and to subscription video on demand (SVOD) services. We consider a monopoly ISP that offers different tiers. We aggregate all SVOD providers that directly interconnect with the ISP. Consumers differ in the utilities they place on broadband service tiers and on SVOD service, and each customer chooses the service which maximizes his/her surplus. We derive the demand of each broadband service tier and of SVOD services, the associated consumer surplus, the associated ISP profit, and aggregated SVOD providers' profit.

We consider a monopoly ISP that offers a basic tier and a premium tier differentiated by download speed, both with data caps, and an add-on that allows unlimited usage. We show the effect of SVOD traffic localization and the number of interconnection points on the monthly marginal costs of the ISP and SVOD providers. We then determine the peering fee that maximizes an ISP's profit. The results indicate that a profit-maximizing ISP may charge SVOD providers the highest amount their willingness to pay permits. Our research reveals that as SVOD traffic localization increases, the peering price that ISPs can demand decreases due to a reduced maximum amount that SVOD providers are willing to pay for peering. Also, our results demonstrate with a low level of localization, the peering fee charged by the profit-maximizing ISP increases as the number of interconnection points rises. However, for a high level of localization, the peering fee charged by the profit-maximizing ISP declines as the number of interconnection points increases. We then compare the cost-based peering fee with the profit-maximizing peering fee. We find that the ISP's profit-maximizing peering fee typically exceeds the cost-based peering fee, and this gap may diminish with increasing traffic localization.

Finally, we examine the potential implications of regulatory oversight on peering prices and unlimited usage add-on fees. We use the term "bundle price" to refer to the combined total of the peering fee and the unlimited usage add-on price. We consider a regulator that wishes to determine the bundle price that maximizes either consumer surplus or social welfare, while the ISP, with its profit-maximizing objectives, determines the pricing for the basic and premium tiers. We show that consumer surplus is a uni-modal function of the bundle price, and that the bundle price that maximizes consumer surplus is substantially less than the bundle price that maximizes ISP profit. We also show the effect of the number of interconnection points and the degree of content localization by SVOD services on the bundle prices that maximize ISP profit, social welfare, and consumer surplus.

8.1 A Model Of User Subscription To Broadband And To Video Streaming

In the previous sections, we determined a cost-based peering fee between a content provider and an ISP. This cost-based peering fee also represents the minimum price an ISP may accept based on the ISP's cost for transporting the content provider's traffic using direct peering versus indirect peering. Indirect peering refers to a network interconnection arrangement where the content provider sends traffic to the ISP through a third-party transit provider, unlike direct peering where the content provider and ISP interconnect directly.

In the remainder of the section, we consider the peering fee that maximizes an ISP's profit. We use a two-sided market model in which a profit-maximizing ISP determines broadband prices and the peering price, and in which content providers determine their service prices based on the peering price.

The range from the cost-based peering fee to the profit-maximizing peering fee determines possible peering fees that the parties may agree to, if unregulated. The lower boundary is shaped by costs, while the upper limit is dictated by profit maximization. The upper limit of this range is the intersection of two components: the peering price that maximizes the ISP's profit, and the content provider's maximum willingness to pay.

In this section, we develop a user subscription model. In the following section, we will introduce a two-sided market model that considers how the ISP chooses charges on both sides of the market: the customers on one side and the content provider on the other.

8.1.1 Service Offerings

Before we can analyze the paid peering prices, we need a model of user subscription to broadband service tiers and to Subscription Video on Demand (SVOD) providers. In [12], we proposed a model of user subscription to broadband and SVOD providers. However, since then, it has become common for large ISPs in the United States to levy an additional charge for unlimited monthly usage. We thus update that model to account for this new charge.

ISPs offer multiple tiers of broadband services, differentiated principally by download speed and amount of data. ISPs typically market these broadband service tiers by recommending specific tiers to consumers who engage in specific types of online activities. For example, Comcast recommends a lower service tier to consumers who principally use their Internet connection for email and web browsing, but a higher service tier to consumers who use the Internet for video streaming.

Many ISPs place a limit on the monthly usage on each service tier. The data caps placed on higher tiers have often been in the range of 1 to 1.25 TB per month, and have not increased substantially in the past few years. When these data caps were originally introduced, few users exceeded them. However, users who engage in substantial subscription video streaming are increasingly hitting these data caps. Indeed, the percentage of users whose usage exceeded 1 TB per month in the fourth quarter of 2022 was 18.7%, which is ten times the percentage observed five years before [94]. Subscribers who exceed these data caps may be charged very high per volume overage fees. In recent years, however, some large ISPs have begun to offer an add-on to each service tier that removes the usage cap. Subscribers with high SVOD usage increasingly purchase this unlimited usage add-on.

Much of the debate over paid peering concerns consumers who stream large volumes of video. Thus, we construct here a model that includes three broadband service tiers: a basic tier with a download speed intended for email and web browsing; a premium tier with a download speed intended for video streaming and gaming and with a data cap that limits the amount of video streaming, and an unlimited premium tier with the same speed as the premium tier but without any data cap. Although some ISPs offer more than three tiers, the majority of customers subscribe to a subset of three tiers, and this three-tier model is sufficient to separately evaluate the effect of paid peering prices on consumers who utilize video streaming and on consumers who don't.

Specifically, we model a single monopoly ISP that offers a basic tier at a monthly price P^b, a limited premium tier at a monthly price $P^b + P^p$, and an unlimited data option for premium tier customers for an extra monthly fee of P^h. We consider N^{pop} consumers, each of whom may subscribe to the basic tier, the limited premium tier, the unlimited premium tier, or to none of these. We denote user i's utility per month from subscription to the basic tier by b_i, and user i's utility per month from subscription to the limited premium tier by $b_i + p_i$.

We focus on the aggregate of all SVOD providers that directly interconnect with the ISP and that may pay (or be paid) a fee for peering with the ISP. We model the aggregate of all plans offered by these SVOD providers, but to keep the model tractable we consider a single price of P^{svod} per month for the aggregate. We presume that a consumer who gains significant utility from SVOD subscribes to the unlimited premium tier, and that all users who subscribe to the unlimited premium tier subscribe to SVOD. As a result, SVOD users pay a total amount of $P^v = P^h + P^{svod}$ to the combination of their ISP and SVOD providers to enable SVOD. We denote user i's utility per month from the combination of subscription to SVOD providers and to the unlimited usage add-on by v_i. Consumer i's utility from all other content is included in $b_i + p_i$.

Consumers differ in the utilities they place on broadband service tiers and on SVOD. We assume that the number of consumers N^{pop} is large, and we denote the joint probability density function of their utilities by $f_{B,P,V}(b, p, v)$.

8.1.2 Demand Functions

Each consumer thus has four choices

$$X_i \triangleq \begin{cases} n, & \text{do not subscribe} \\ b, & \text{subscribe to the basic tier} \\ p, & \text{subscribe to the limited premium tier} \\ v, & \text{subscribe to the unlimited premium tier and to SVOD.} \end{cases} \tag{8.1}$$

Consumer i's consumer surplus, defined as utility minus cost, under each choice is thus

$$CS_i(X_i; b_i, p_i, v_i) = \begin{cases} 0, & X_i = n \\ b_i - P^b, & X_i = b \\ b_i + p_i - P^b - P^p, & X_i = p \\ b_i + p_i + v_i - P^b - P^p - P^v, & X_i = v. \end{cases} \tag{8.2}$$

Each consumer is assumed to maximize consumer surplus. Thus, consumer i adopts the choice

$$X_i^*(b_i, p_i, v_i) \triangleq \arg\max_{X_i} CS_i(X_i; b_i, p_i, v_i), \tag{8.3}$$

and earns a corresponding consumer surplus $CS_i^* \triangleq CS_i(X_i^*)$.

Each of the N consumers makes an individual choice per (8.3). The consumers who choose to subscribe to the basic tier are those whose utility b_i from subscription to the basic tier exceeds its monthly price P^b, whose incremental utility p_i from subscription to the limited premium tier falls below the incremental monthly price P^p, and whose incremental utility $p_i + v_i$ from subscription to the unlimited premium tier and to SVOD falls below the corresponding incremental monthly price $P^p + P^v$. Thus, the demand[1] for the basic tier is given by:

$$\begin{aligned} &N^b(P^b, P^p, P^v) = \\ &N \int_{-\infty}^{P^p} \int_{-\infty}^{P^p+P^v-p} \int_{P^b}^{\infty} f_{B,P,V}(b, p, v)\ db\ dv\ dp. \end{aligned} \tag{8.4}$$

Similarly, the consumers who choose to subscribe to the limited premium tier are those whose utility $b_i + p_i$ from subscription to the limited premium tier exceeds its monthly price $P^b + P^p$, whose incremental utility p_i from subscription to the limited premium tier exceeds the incremental monthly price P^p, and whose incremental utility v_i from subscription to unlimited premium tier and to SVOD falls below the incremental monthly price P^v. Thus, the number of consumers who subscribe to the limited premium tier is given by:

$$\begin{aligned} &N^p(P^b, P^p, P^v) = \\ &N \int_{-\infty}^{P^v} \int_{P^p}^{\infty} \int_{P^b+P^p-p}^{\infty} f_{B,P,V}(b, p, v)\ db\ dp\ dv. \end{aligned} \tag{8.5}$$

Finally, the consumers who choose to subscribe to the unlimited premium tier and to SVOD are those whose utility $b_i + p_i + v_i$ from subscription to both services exceeds the combined cost $P^b + P^p + P^v$, whose incremental utility $p_i + v_i$ from subscription to only the basic tier exceeds the corresponding incremental price $P^p + P^v$, and whose incremental utility v_i from subscription to SVOD falls exceeds the incremental monthly price P^v. Thus, the demand for the unlimited premium tier is given by:

$$\begin{aligned} &N^v(P^b, P^p, P^v) = \\ &N \int_{P^v}^{\infty} \int_{P^p+P^v-v}^{\infty} \int_{P^b+P^p+P^v-p-v}^{\infty} f_{B,P,V}(b, p, v)\ db\ dp\ dv. \end{aligned} \tag{8.6}$$

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[1] Since we model a finite number N of consumers whose utilities are given by a joint probability density function, this equation, and other similar equations below, give the *average demand*. However, for simplicity of presentation, we use the term *demand*.

8.1.3 Consumer Surplus

The aggregate consumer surplus will be an important quantity to consider in our deliberations below. It can be easily determined for each set of consumers using the number of subscribers in each set (8.4-8.6) and the surplus of each consumer (8.2). Given a set of prices, the aggregate consumer surplus of subscribers to the basic tier is

$$\begin{aligned} &CS^b(P^b, P^p, P^v) = \\ &N \int_{-\infty}^{P^p} \int_{-\infty}^{P^p+P^v-p} \int_{P^b}^{\infty} (b - P^b) f_{B,P,V}(b, p, v)\, db\, dv\, dp. \end{aligned} \tag{8.7}$$

Similarly, the aggregate consumer surplus of consumers who subscribe to the premium tier but not to video streaming is

$$\begin{aligned} &CS^p(P^b, P^p, P^v) = \\ &N \int_{-\infty}^{P^v} \int_{P^p}^{\infty} \int_{P^b+P^p-p}^{\infty} (b + p - P^b - P^p) f_{B,P,V}(b, p, v)\, db\, dp\, dv, \end{aligned} \tag{8.8}$$

and the aggregate consumer surplus of consumers who subscribe to both the premium tier and video streaming is

$$\begin{aligned} &CS^v(P^b, P^p, P^v) = N \int_{P^v}^{\infty} \int_{P^p+P^v-v}^{\infty} \int_{P^b+P^p+P^v-p-v}^{\infty} \\ &(b + p + v - P^b - P^p - P^v) f_{B,P,V}(b, p, v)\, db\, dp\, dv. \end{aligned} \tag{8.9}$$

The aggregate consumer surplus over all consumers is defined as

$$\begin{aligned} &CS(P^b, P^p, P^v) \triangleq \\ &CS^b(P^b, P^p, P^v) + CS^p(P^b, P^p, P^v) + CS^v(P^b, P^p, P^v) \end{aligned} \tag{8.10}$$

8.1.4 Profits

We assume that the ISP incurs a monthly marginal cost C^b per basic tier subscriber. The ISP marginal profit per basic tier subscriber is thus $P^b - C^b$. We assume that the ISP incurs a monthly marginal cost $C^b + C^p$ per limited premium tier subscriber. The ISP marginal profit per such broadband service tier subscriber is thus $P^b + P^p - C^b - C^p$. We associate an ISP monthly marginal cost $C^b + C^p + C^v$ per unlimited premium tier customer.

We also consider a peering price of P^d per SVOD subscriber for direct interconnection between the ISP and SVOD providers. This price may be positive if the ISP charges SVOD providers for direct interconnection, negative if the SVOD providers charge the ISP for direct interconnection, or zero if the peering is settlement-free.

The ISP marginal profit per SVOD subscriber is $P^b + P^p + P^h + P^d - C^b - C^p - C^v$. The total ISP profit (excluding fixed costs)[2] is thus

$$\begin{aligned} &\pi^{ISP}(P^b, P^p, P^h, P^d, P^{svod}) \\ &= (P^b - C^b)N^b + (P^b + P^p - C^b - C^p)N^p \\ &+ (P^b + P^p + P^h + P^d - C^b - C^p - C^v)N^v. \end{aligned} \tag{8.11}$$

We assume that the SVOD providers incur a monthly marginal cost C^{svod} per subscriber. The aggregate SVOD provider marginal profit per subscriber is thus $P^{svod} - C^{svod} - P^d$, and their total profit is:

$$\pi^{SVOD}(P^b, P^p, P^h, P^d, P^{svod}) = (P^{svod} - C^{svod} - P^d)N^v. \tag{8.12}$$

where P^{svod} is the aggregate monthly SVOD providers price.

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[2] Throughout the section, ISP profit accounts for costs that are sensitive to the number of subscribers and/or the amount of traffic, but does not account for costs that are fixed with respect to both the number of subscribers and the amount of traffic.

We assume that the market determines the aggregate SVOD price, excluding paid peering fees, when there is no regulation of prices. We denote the aggregate SVOD price, excluding paid peering fees, by P_0^v. We presume that an ISP charging peering prices would likely charge them to both directly interconnected content providers and directly interconnected transit providers. We further presume that transit providers would pass peering prices through to their customers. As a consequence, we foresee that peering prices would be paid by all large SVOD providers selling to the ISP's customers. An open question is whether the SVOD providers can pass through any peering price (P^d) to their customers by adding it to their SVOD prices. We denote the pass-through rate of the peering fee by $0 < \alpha \leq 1$:

$$P^{svod}(P^d) = P_0^v + \alpha P^d. \tag{8.13}$$

Hence, we can reformulate SVOD profit as:

$$\pi^{SVOD}(P^b, P^p, P^h, P^d) = (P_0^v - C^{svod} + (\alpha - 1)P^d)N^v. \tag{8.14}$$

8.1.5 Costs

In order to understand the effect of the number of interconnection points and SVOD traffic localization on peering agreements between the ISP and SVOD providers, we first analyze the monthly marginal costs [3].

We partition traffic-related costs into three categories based on the associated costs and usage:

- Subscription Video on Demand (SVOD) traffic: traffic generated by subscription-based video streaming platforms such as Netflix, Disney+, Amazon Prime, and Hulu.

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[3] The analysis provided focuses solely on the backbone costs incurred by ISPs and does not encompass the localization costs associated with CDNs.

- Premium traffic: video and gaming traffic that isn't generated by SVOD providers, including traffic from non-subscription video streaming, online multiplayer gaming, live-streaming platforms, video conferencing, and other high-bandwidth activities.
- Basic traffic: all Internet traffic that isn't included in the SVOD or premium traffic categories, including traffic from web browsing, email, social media, downloading or uploading files, and other common online activities that don't typically require high bandwidth or produce large amounts of data traffic.

Our assumption is that basic tier subscribers only transmit and receive basic traffic, limited premium tier subscribers transmit and receive both basic and premium traffic, and unlimited premium tier subscribers transmit and receive all types of traffic.

The ISP exchanges basic traffic through a transit provider. We assume that the ISP and the transit provider interconnect at the $M = 12$ major interconnection points, and that both use hot potato routing. We consider downstream basic traffic originating on the transit provider's network destined for an end user located in the ISP's network, and denote the volume of this traffic by V^b_{down}. We also consider upstream basic traffic originating with an end user located in the ISP's network and destined for a location on the transit provider's network, and denote the volume of this traffic by V^b_{up}. The monthly marginal cost C^b per basic tier subscriber can be defined as:

$$\begin{aligned} C^b = {} & c^b(\overline{V}^b_{down} ED^{hot}_{down}(M) + \overline{V}^b_{up} ED^{cold}_{down}(M)) \\ & + (\overline{V}^b_{down} + \overline{V}^b_{up})(c^m ED^m + c^a ED^a) + C^f_{ISP}, \end{aligned} \tag{8.15}$$

where $\overline{V}^b_{down}$ is the average usage of downstream basic traffic among all ISP customers, $\overline{V}^b_{up}$ is the average usage of upstream basic traffic among all ISP customers, $ED^{hot}_{down}(M)$ is the average distance of basic traffic on the ISP's backbone network using hot potato routing, $ED^{cold}_{down}(M)$ is the average distance of basic traffic on the ISP's backbone network using cold potato routing, ED^m is the average distance of basic traffic on the ISP's middle network, ED^a is the average distance of basic traffic on the ISP's access network, and C^f_{ISP} is the non-traffic sensitive monthly marginal cost per basic tier subscriber.

The ISP also exchanges premium traffic (which excludes SVOD services that interconnect directly to the ISP) through the transit provider. Denote the volume of the downstream premium traffic by V^p_{down} and the volume of the upstream premium traffic by V^p_{up}. Recall that the monthly marginal cost per limited premium tier subscriber is $C^b + C^p$. Now C^b is given in (8.15), since limited premium tier subscribers transmit and receive the same volume of basic traffic as do basic tier subscribers. However, they also transmit and receive premium traffic, and this marginal traffic-sensitive cost is:

$$\begin{aligned} C^p &= c^b(\overline{V}^p_{down} ED^{hot}_{down}(M) + \overline{V}^p_{up} ED^{cold}_{down}(M)) \\ &\quad + (\overline{V}^p_{down} + \overline{V}^p_{up})(c^m ED^m + c^a ED^a), \end{aligned} \tag{8.16}$$

where $\overline{V}^p_{down}$ is the average usage of downstream premium traffic among all premium tier customers and $\overline{V}^p_{up}$ is the average usage of upstream premium traffic among all premium tier customers.

The ISP receives SVOD traffic through peering with SVOD providers. Peering between SVOD providers and the ISP differs from peering between a transit provider and an ISP for three reasons. First, we assume that the SVOD provider has deployed content servers at N major interconnection points, and that N may be less than the number of interconnection points at which the transit provider and the ISP agree to peer (M). Second, the SVOD provider may localize a proportion of SVOD traffic. We assume that a proportion x^d of the SVOD traffic transmitted to the ISP's users within each access network is delivered from the SVOD provider at a server located at the IXP nearest to the end user among the IXPs at which they agree to peer. We assume that the remaining proportion $1 - x^d$ of the SVOD traffic transmitted to the ISP's users within each access network is delivered using any SVOD server, and that the location of this SVOD provider's server is independent of the location of the end user. Third, SVOD providers carry only downstream SVOD traffic. We denote the volume of downstream SVOD traffic by V^v_{down}.

Recall that the monthly marginal cost per unlimited premium tier subscriber is $C^b + C^p + C^v$. Now C^b is given in (8.15) and C^p is given in (8.16), since unlimited premium tier subscribers transmit and receive the same volume of basic and premium traffic as do limited premium tier subscribers. However, they also receive SVOD traffic, and this marginal traffic-sensitive cost is:

$$\begin{aligned} C^v &= c^b \overline{V}^v_{down} \Big(x^d ED^{cold}_{down}(N) + (1 - x^d) ED^{hot}_{down}(N) \Big) \\ &\quad + \overline{V}^v_{down} (c^m ED^m + c^a ED^a), \end{aligned} \tag{8.17}$$

where $\overline{V}^v_{down}$ is the average usage of SVOD among all SVOD subscribers.

We must address whether an ISP should recover the incremental ISP cost C^v per SVOD subscriber across different parts of its network solely from its subscribers or also from interconnecting networks. We propose that customers bear middle-mile and access network costs related to SVOD traffic (denoted by C^h), and that SVOD providers bear ISP backbone costs related to SVOD traffic (denoted by C^d), where $C^v = C^h + C^d$.

The first term in (8.17) is the ISP backbone cost related to SVOD traffic per SVOD subscriber:

$$C^d = c^b \overline{V}^v_{down} \Big(x^d ED^{cold}_{down}(N) + (1 - x^d) ED^{hot}_{down}(N) \Big), \tag{8.18}$$

and the second term in (8.17) is the middle-mile and access network cost related to SVOD traffic per SVOD subscriber:

$$C^h = \overline{V}^v_{down} (c^m ED^m + c^a ED^a). \tag{8.19}$$

We now turn to the SVOD providers' costs. Recall that we assume that a proportion x^d of the SVOD traffic transmitted to the ISP's users within each access network is delivered from the SVOD provider at a server located at the IXP nearest to the end user among the IXPs at which they agree to peer. If SVOD providers were to localize this traffic by using cold potato routing, then their the monthly marginal cost per SVOD subscriber incurred by the SVOD providers would be:

$$\begin{aligned} &C^{svod} = \\ &c^b \overline{V}^v_{down} \Big(x^d ED^{hot}_{down}(N) + (1 - x^d) ED^{cold}_{down}(N) \Big) + C^f_{SVOD}, \end{aligned} \tag{8.20}$$

where C^f_{SVOD} is the non-traffic sensitive monthly marginal cost per SVOD subscriber. The first term is the SVOD's backbone cost for localized SVOD traffic, which the SVOD providers deliver using cold potato routing. The second term is the SVOD providers' backbone cost for non-localized SVOD traffic, which the SVOD providers deliver using hot potato routing.

That said, it is common for SVOD providers to utilize CDN (Content Delivery Network) services to localize traffic, instead of using cold potato routing, if this reduces their costs. In future research, we will propose a cost model for SVOD providers using CDNs. In this section, we simply consider (8.20) to be an upper bound for SVOD provider costs.

Figure 8.1 shows the effect of SVOD traffic localization (x^d) and the number of interconnection points (N) on the backbone costs of the ISP (C^d) and of SVOD providers (C^{svod}) related to SVOD traffic. As the amount of SVOD traffic localization (x^d) increases, the ISP cost C^d is decreasing and the SVOD cost C^{svod} is increasing, because increasing localization results in the SVOD providers carrying more of the SVOD traffic on their backbone networks and handing it off to the ISP at an IXP closer to end users.

The costs of the ISP and SVOD providers also vary with the number of IXPs at which they agree to peer. When localization is very low, interconnecting at more IXPs is not beneficial

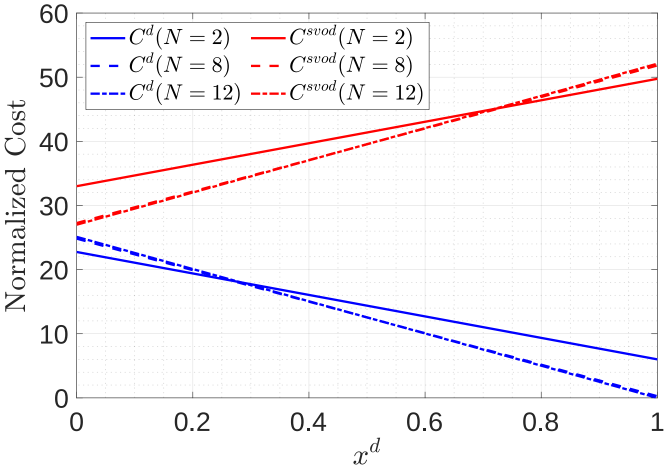

Figure 8.1: Effect of localization and number of IXPs on C^d and C^{svod}

to the ISP, because the ISP needs to carry the SVOD traffic over longer distances in its backbone network since the peering IXP moves farther from the IXP nearest to the end user [95]. Therefore, the ISP cost (C^d) increases slightly with N at very low amounts of localization. However, it is beneficial for the SVOD provider to peer at more IXPs when the localization is very low since the peering IXP moves closer to the IXP nearest to the source. Therefore, the SVOD cost (C^{svod}) decreases with N at low amounts of localization.

For moderate to high localization, interconnecting at more IXPs is beneficial to the ISP and the ISP's cost (C^d) decreases since the peering IXP moves closer to the IXP nearest to the end user [95]. However, it is not beneficial to the SVOD provider since interconnecting at more IXPs with a high amount of traffic localization increases the SVOD cost (C^{svod}) since the peering IXP moves farther from the IXP nearest to the source.

8.2 Peering Between A Content Provider And A Profit-Maximizing ISP

The previous section presented a model for consumer demand for broadband Internet access service and for SVOD services, and the corresponding ISP and SVOD provider profits (8.11-8.14). There are a number of options for modeling how the broadband service tier prices (P^b, P^p, and P^h), the aggregate SVOD price (P^{svod}), and the peering price (P^d) are determined. In this section, we explore the determination of prices when the ISP aims to maximize its profit.

8.2.1 Numerical Parameters

This two-sided model is somewhat amenable to closed-form analysis. However, we find it useful to also examine the model under a set of realistically chosen parameters. We set out those parameters in this subsection [4].

The joint probability density function of user utilities for the basic tier, the limited premium tier, and the unlimited premium is represented by $f_{B,P,V}(b,p,v)$. For numerical evaluation, we assume that each utility is independent and has a Normal distribution: $B \sim \mathcal{N}(\mu_b,\, \sigma_b^2), P \sim \mathcal{N}(\mu_p,\, \sigma_p^2), V \sim \mathcal{N}(\mu_v,\, \sigma_v^2)$. We need to determine numerical values for the means and variances.

The ISP incurs a monthly marginal cost of C^b per subscriber, a monthly incremental cost of C^p per premium tier subscriber, and a monthly incremental cost C^v per SVOD subscriber. We need to determine numerical values for these three costs.

Unfortunately, direct information about user utilities and ISP costs is scarce. Instead, we

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[4] Although the numerical results depend on the numerical values of these parameters, all of the qualitative results presented in this section remain true for all parameter ranges that we analyzed.

choose numerical values for user utilities and ISP costs indirectly using available information about demand and prices in the United States.

There are several sets of publicly available statistics about broadband prices and subscriptions [79, 96–98]. While the set of statistics differ, they show that roughly 85% of households in the United States subscribe to broadband service. Of subscribers, 19.5% subscribe to plans with download speeds below 100 Mbps, 61.8% subscribe to plans with download speeds above 100 Mbps but consume less than 1 TB of data, and 18.7% subscribe to plans with download speeds above 100 Mbps and consume over 1 TB of data [94]. Hence, we wish to choose numerical values for user utilities and ISP costs so that, at the ISP profit-maximizing prices, $(N^b + N^p + N^v)/N = 0.85$, $N^b/(N^b + N^p + N^v) = 0.195$, $N^p/(N^b + N^p + N^v) = 0.618$, and $N^v/(N^b + N^p + N^v) = 0.187$.

Moreover, upon reviewing the plan and pricing web pages of major ISPs [99–101], we find that the price of the lower of the two most popular tiers is roughly \$61 per month, the price of the higher of the two most popular tiers is roughly \$83 per month, and the price of an unlimited usage add-on is roughly \$30 per month. Hence, we wish to choose numerical values for user utilities and ISP costs so that the ISP profit-maximizing prices are $P^b = \$61.00$, $P^p = \$22.00$, and $P^h = \$30.00$.

According to [102], Americans subscribe to an average of four SVOD providers. In our model, we assume that these four SVOD providers directly interconnect with the ISP. Additionally, the average monthly payment for SVOD in the United States is approximately \$54 [103]. In addition, although we consider any pass-through rate of the paid peering fee ($0 < \alpha \leq 1$), in the numerical results below we use $\alpha = 0.5$. Therefore, we assign an aggregate SVOD price, excluding paid peering fees $P_0^v = \$50$ in our model to achieve $P^{svod} = 54$ where the ISP chooses the peering price that maximizes its profit.

The average household usage is approximately 600 GB [94]. The combined traffic generated by Netflix, Disney+, Amazon Prime, and Hulu accounts for 31.6% of downstream traffic and 6.17% of upstream traffic [104]. Additionally, video and gaming traffic, excluding the aforementioned video-on-demand services, represents 50.82% of downstream traffic and 36.82% of upstream traffic [104]. The remaining 17.58% of downstream traffic and 57.01% of upstream traffic corresponds to other basic traffic [104]. Furthermore, roughly 6% of the total traffic is attributed to upstream traffic [104].

Let $\overline{V}^v$ represent the average usage of SVOD traffic (traffic generated by Netflix, Disney+, Amazon Prime, and Hulu) among subscribers who are on the unlimited premium tier plan. Similarly, let $\overline{V}^p$ denote the average usage of premium traffic (including video and gaming traffic, excluding the previously mentioned SVOD providers) among all customers on the premium tier, regardless of whether or not they have data caps. Finally, $\overline{V}^b$ denotes the average usage of basic traffic among all customers of the ISP.[5]

Let's consider the following traffic values:

$$
\begin{aligned}
\overline{V}^b_{up} &= \frac{V^b_{up}}{N^b + N^p + N^v} = \frac{(600)(0.06)(57.01)}{18.7 + 61.8 + 19.5} = 21\ GB \\
\overline{V}^p_{up} &= \frac{V^p_{up}}{N^p + N^v} = \frac{(600)(0.06)(36.82)}{18.7 + 61.8} = 16\ GB \\
\overline{V}^v_{up} &= \frac{V^v_{up}}{N^v} = \frac{(600)(0.06)(6.17)}{18.7} = 12 \\
\overline{V}^b_{down} &= \frac{V^b_{down}}{N^b + N^p + N^v} = \frac{(600)(0.94)(17.58)}{18.7 + 61.8 + 19.5} = 99\ GB \\
\overline{V}^p_{down} &= \frac{V^p_{down}}{N^p + N^v} = \frac{(600)(0.94)(50.82)}{18.7 + 61.8} = 356\ GB \\
\overline{V}^v_{down} &= \frac{V^v_{down}}{N^v} = \frac{(600)(0.94)(31.6)}{18.7} = 953\ GB.
\end{aligned}
\tag{8.21}
$$

We use these parameters in the remainder of the section except as noted.

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[5] Given that video traffic from large streaming providers typically has significantly more downstream traffic than upstream traffic (approximately 80 times more), the cost of upstream traffic is not taken into consideration for those subscribers in our model.

8.2.2 Peering Fee

Let's begin by considering the scenario in which the ISP selects all its prices in order to maximize its profit.

Once a subscriber chooses an ISP, the ISP has a monopoly on the transport of traffic within the ISP's access network that the customer resides in. In contrast, there may be a competitive market for the transport of Internet traffic across backbone networks. Correspondingly, we assume that the ISP has the market power to determine the broadband service tier prices (P^b and P^p), unlimited usage add-on price (P^h), and the peering price (P^d) to maximize its profit. However, there is a constraint on these prices given by SVOD providers earning a positive profit. The resulting optimization problem is:

$$\begin{aligned}
&(P^b_{ISP}, P^p_{ISP}, P^h_{ISP}, P^d_{ISP}) = \\
&\arg \max_{(P^b, P^p, P^h, P^d)} \pi^{ISP}(P^b, P^p, P^h, P^d, P^{svod}) \\
&\text{s.t.} \\
&\pi^{SVOD}(P^b, P^p, P^h, P^d, P^{svod}) \geq 0.
\end{aligned} \tag{8.22}$$

Equations (8.13) and (8.22) set up a two-sided model in which the ISP earns revenue from both its customers and SVOD providers (if $P^d > 0$). The combination of the two equations captures the inter-dependencies between the ISP, the SVOD providers, and the consumers. The ISP-determined peering price (P^d), along with the pass-through rate (α), leads to an aggregate SVOD price (P^{svod}). The ISP-determined broadband service tier prices (P^b and P^p), unlimited usage add-on price (P^h), and the aggregate SVOD price (P^{svod}) lead to demands for each broadband service tier (N^b and N^p) and for SVOD services (N^v). These demands in turn affect how the ISP sets each of the prices.

Since the aggregate SVOD price (P^{svod}) is solely determined by (8.13), we can represent the

ISP's profit as a function of four variables rather than five:

$$\begin{aligned}&(P^b_{ISP}, P^p_{ISP}, P^h_{ISP}, P^d_{ISP}) =\\&\arg\max_{(P^b,P^p,P^h,P^d)} \pi^{ISP}(P^b, P^p, P^h, P^d, P^v_0 + \alpha P^d)\\&\text{s.t.}\\&(P^v_0 - (1-\alpha)P^d - C^{svod})N^v \geq 0.\end{aligned} \tag{8.23}$$

As will be demonstrated by the numerical results [6], the profit-maximizing ISP would set the peering fee at the maximum amount that SVOD providers are willing to pay [7].

$$\begin{aligned}&\pi^{SVOD}(P^b, P^p, P^h, P^d) =\\&(P^v_0 - (1-\alpha)P^d - C^{svod})N^v = 0\end{aligned} \tag{8.24}$$

The peering fee that maximizes the ISP's profit, while considering the SVOD providers' willingness to pay, is determined as follows:

$$P^d_{ISP} = \frac{P^v_0 - C^{svod}}{1-\alpha}. \tag{8.25}$$

By utilizing the upper bound on C^{svod} given in (8.20), we can formulate the peering price as a function of number of interconnection points and the localization of SVOD traffic:

$$\begin{aligned}&P^d_{ISP} =\\&\frac{P^v_0 - C^f_{SVOD} - c^b\overline{V}^v_{down}\Big(x^d ED^{hot}_{down}(N) + (1-x^d)ED^{cold}_{down}(N)\Big)}{1-\alpha}.\end{aligned} \tag{8.26}$$

---

[6] Our methodology is designed with computational efficiency in mind, enabling it to be executed within a few hours even without compilation.

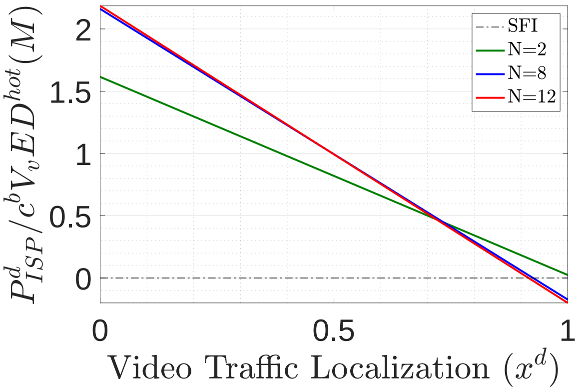
[7] The optimization problems here can be solved numerically using standard optimization algorithms for maximization of a nonlinear function with nonlinear constraints

Note, however, that because (8.20) is an upper bound on SVOD costs, (8.26) represents a lower bound on the profit-maximizing peering price P^d.

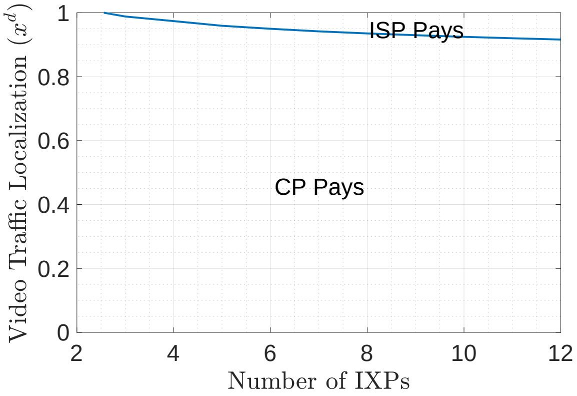
Figure 8.2(a) illustrates the effect of SVOD traffic localization on the peering price (per SVOD provider) between a profit-maximizing ISP and the SVOD provider. As an SVOD provider increases the localization of its traffic, its cost (C^{svod}) increases. However, this increase in the SVOD cost results in a decrease in SVOD profit, thereby lowering the maximum amount the SVOD provider is willing to pay for peering. Consequently, with the rise in SVOD traffic localization, the peering price P^d that the ISP can demand decreases.

Figure 8.2(a) also illustrates the effect of the number of interconnection points on the peering price. As previously discussed in subsection 8.1.5, when there is a low level of localization, the cost for the SVOD provider (C^{svod}) decreases as the number of interconnection points increases. This decrease in cost raises both the profit and willingness to pay of the SVOD provider. As a result, with a low level of localization, the peering fee charged by the profit-maximizing ISP increases as the number of interconnection points rises. In contrast, with a high level of localization, the cost of the SVOD provider (C^{svod}) increases as the number of interconnection points rises. This leads to a decrease in both the profit and willingness to pay of the SVOD provider. Therefore, for a high level of localization, the peering fee charged by the profit-maximizing ISP declines as the number of interconnection points increases. Moreover, our findings suggest that there is little effect of interconnecting at more than 8 IXPs on the peering fee.

At very high levels of video traffic localization, the ISP maximizes profit by paying a negative peering fee, namely by paying SVOD providers for direct interconnection. At these levels, the ISP's backbone cost is minimal, and the SVOD provider's cost is high. As a consequence, without a small payment from the ISP to the SVOD providers, the SVOD providers can not offer this level of localization. The ISP is willing to offer this small payment in order to maintain its significant profit from its unlimited tier subscribers.



(a) Peering Fee



(b) Settlement-Free Curve

Figure 8.2: Peering between an SVOD provider and a profit-maximizing ISP

Figure 8.2(b) illustrates the settlement-free peering curve for direct interconnection between the SVOD provider and an ISP, as a function of the amount of SVOD traffic localization and the number of IXPs at which they peer. The curve is given by:

$$x^d = \frac{\frac{P_0^v - C_{SVOD}^f}{c^b \overline{V}_{down}^v} - ED_{down}^{cold}(N)}{ED_{down}^{hot}(N) - ED_{down}^{cold}(N)}. \tag{8.27}$$

Finally, we examine the range from the cost-based peering fee to the profit-maximizing peering fee. The cost-based peering fee, illustrated in Figure 6.3, represents the minimum price an ISP may accept based on the ISP's cost for transporting the content provider's traffic using direct peering versus indirect peering. The profit-maximizing peering fee, illustrated in Figure 8.2, represents the maximum price a content provider may be willing to pay the ISP.

Comparing Figure 6.3 and Figure 8.2(a), we unsurprisingly find that the ISP profit-maximizing peering fee exceeds the cost-based peering fee for all values of video traffic localization. When the ISP and a content provider interconnect at a minimum of 8 IXPs, at low levels of localization the profit-maximizing peering fee may exceed the cost-based peering fee by over \$1.50 per SVOD provider per SVOD customer. This gap may diminish with increasing localization, but a CDN cost model is required to confirm this.

Comparing Figure 6.4 and Figure 8.2(b), we find that when an ISP sets the peering fee to maximize profit, it is very likely to set this price to be greater than zero. In contrast, the cost-based peering fee may be zero (or negative) if the content provider localizes at least 50%-60% of its traffic.

8.3 Regulatory Oversight And Implications For Peering Prices

In this section, we delve into a critical analysis of how regulatory oversight of the peering price and the unlimited usage add-on price could influence consumer surplus and societal welfare. By comparing an unregulated approach (e.g., ISP profit maximization) with regulatory approaches (e.g., maximizing consumer surplus or social welfare), we hope to gain an understanding of the potential outcomes of such regulatory interventions. Through this analysis, we seek to identify the peering price within the established range that maximizes either consumer surplus or social welfare.

Consider a regulator that wishes to determine the peering price and the unlimited usage add-on price that maximizes either consumer surplus or social welfare. In such instances, the ISP selects P^b and P^p to maximize its profit, while the regulator determines P^d and P^h to maximize consumer surplus or social welfare. When $\alpha = 1$, it is crucial to note that the ISP, video service providers, and consumers are not directly concerned with the individual values of P^d and P^h. Rather, their focus is on the sum $P^d + P^h$. We use the term "bundle price" to refer to the combined total $P^d + P^h$ of the peering fee and the unlimited usage add-on price. Referring to equations (8.4-8.6), we observe that the demand functions are dependent on the combined price P^v of the SVOD price and the unlimited usage add-on price. Similarly, from equation (8.11), it is evident that the ISP's profit hinges on both $P^d + P^h$ and P^v. Furthermore, the SVOD profit, as deduced from equation (8.14), is reliant on the demand for the unlimited premium tier N^v, which in turn is influenced by the combined price P^v of the SVOD price and the unlimited usage add-on price. This chain of dependencies extends to consumer surplus, which is also a function of P^v. Given that for $\alpha = 1$, $P^v = P^h + P^{svod} = P^v_0 + P^d + P^h$, it becomes apparent that all involved parties are essentially concerned with the sum $P^d + P^h$. Consequently, the regulator is presumed to have control over the combined pricing of these two components, while the ISP, with its profit-maximizing objectives, determines the pricing for the basic and premium tiers.

First, consider the case in which the regulator sets $P^d + P^h$ so that it maximizes aggregate consumer surplus:

$$\begin{aligned}
&(P^b_{CS_{reg}}, P^p_{CS_{reg}}) = \\
&\arg\max_{(P^b,P^p)} \pi^{ISP}(P^b, P^p, P^d_{CS_{reg}} + P^h_{CS_{reg}}) \\
&P^d_{CS_{reg}} + P^h_{CS_{reg}} = \\
&\arg\max_{P^d+P^h} CS(P^b_{CS_{reg}}, P^p_{CS_{reg}}, P^d + P^h).
\end{aligned} \tag{8.28}$$

Equation (8.28) determines the resulting aggregate consumer surplus maximizing value of $P^d + P^h$, as well as the resulting broadband prices P^b and P^p and video streaming price P^{svod}.

Another optimization metric commonly used is aggregate social welfare, which we define here as

$$\begin{aligned}
&W(P^b, P^p, P^d + P^h) \triangleq \\
&CS(P^b, P^p, P^d + P^h) + \pi^{ISP}(P^b, P^p, P^d + P^h) \\
&+ \pi^{VSP}(P^b, P^p, P^d + P^h).
\end{aligned} \tag{8.29}$$

Note that whereas the ISP profit maximization problem (8.23) considers only ISP profit, and the aggregate consumer surplus maximization problem (8.28) considers only consumer surplus, social welfare includes both ISP profit and consumer surplus, as well as aggregate video streaming provider profit.

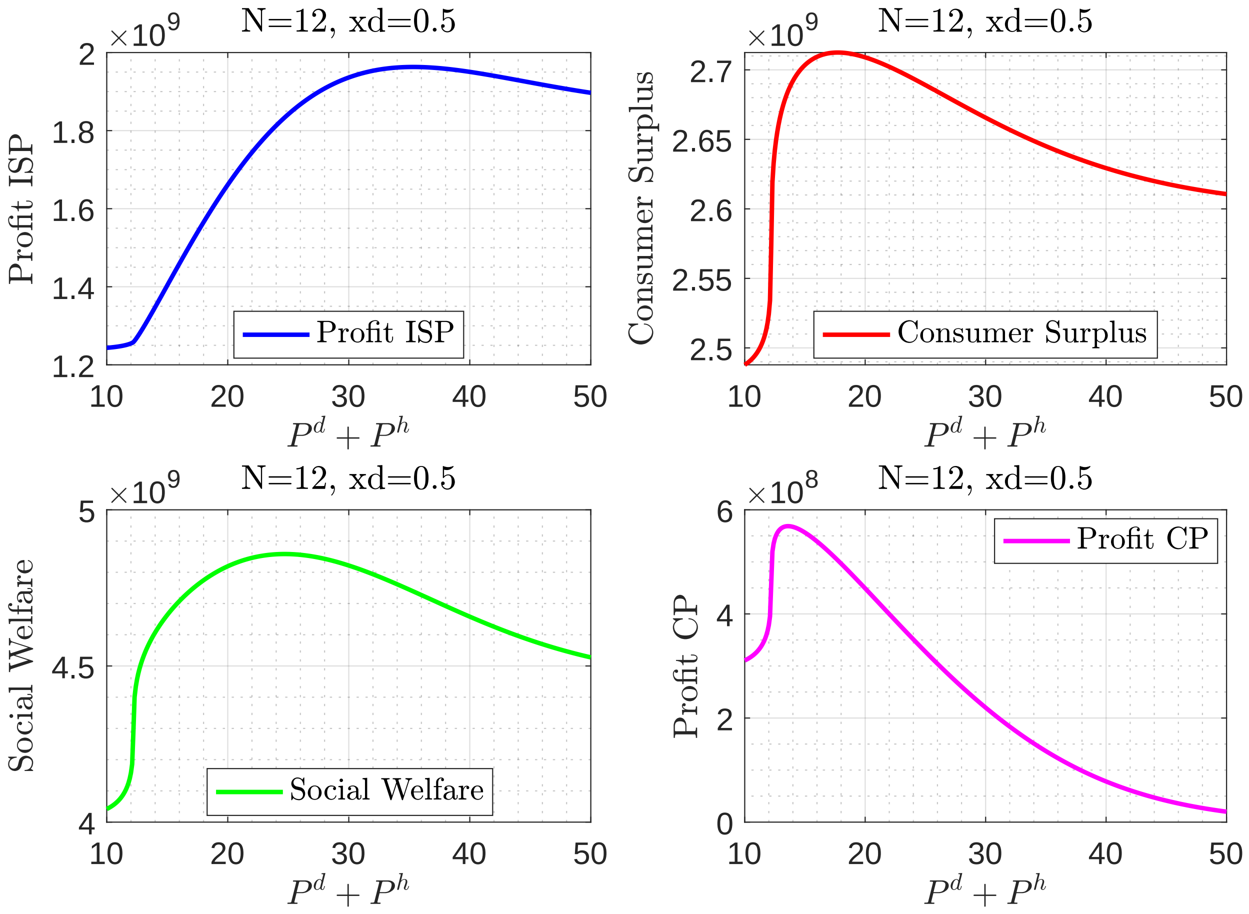


Figure 8.3: Effect of $P^d + P^h$ on ISP, SVODs, and Consumers

The social welfare maximization problem is:

$$
\begin{aligned}
&(P^b_{W_{reg}}, P^p_{W_{reg}}) = \\
&\arg\max_{(P^b,P^b)} \pi^{ISP}(P^b, P^p, P^d_{W_{reg}} + P^h_{W_{reg}}) \\
&P^d_{W_{reg}} + P^h_{W_{reg}} = \\
&\arg\max_{P^d+P^h} W(P^b_{W_{reg}}, P^p_{W_{reg}}, P^d + P^h).
\end{aligned}
\tag{8.30}
$$

We will turn back to our numerical evaluation. Figure 8.3 illustrates the impact of the regulator's chosen value of the bundle price $P^d + P^h$ on various parties, including ISP profit, SVOD profit, consumer surplus, and social welfare, given the parameters $N = 12$ and $x^d =$

0.5. It is important to note that the ISP determines P^b and P^p to maximize its own profit. Aggregate consumer surplus is a uni-modal function of $P^d + P^h$, reaching its peak when $P^d_{CS_{reg}} + P^h_{CS_{reg}} = \$17.70$. This bundle price is significantly lower than the $P^d_{ISP} + P^h_{ISP} = \$35.40$ that maximizes ISP profit. Meanwhile, the bundle price that leads to the highest social welfare is $P^d_{W_{reg}} + P^h_{W_{reg}} = \$24.70$, positioning it between the consumer surplus and ISP profit maximizing prices. When the bundle price falls below \$17.70, the aggregate consumer surplus primarily declines due to an elevated P^p, adversely affecting the surplus of premium tier subscribers. Conversely, bundle prices above \$17.70 result in a reduction in aggregate consumer surplus primarily due to the inflated price of video streaming and the unlimited usage add-on price, negatively impacting the surplus of unlimited premium tier customers.

Figure 8.4 shows the effect of the number of interconnection points (N) and the degree of content localization by SVOD services (x^d) on the bundle prices that maximize ISP profit, social welfare, and consumer surplus. As anticipated, the bundle price ($P^d + P^h$) that maximizes social welfare consistently falls between the consumer surplus maximizing price and the ISP profit maximizing price. Moreover, the prices selected by the regulator to maximize consumer surplus are substantially lower than the prices set by the ISP to maximize its profit.

The impact of the number of IXPs and the extent of localization on the costs incurred by ISPs and SVOD services was previously illustrated in Figure 8.1. As an SVOD provider increases the localization of its traffic, its cost (C^{svod}) increases. However, this increase in the SVOD cost results in a decrease in SVOD profit, thereby lowering the maximum amount the SVOD provider is willing to pay for peering. Consequently, with the rise in SVOD traffic localization, the bundle price $P^d + P^h$ decreases under all pricing policies. Figure 8.4 also illustrates the effect of the number of interconnection points on the peering price. As previously discussed in subsection 8.1.5, when there is a low level of localization, the cost

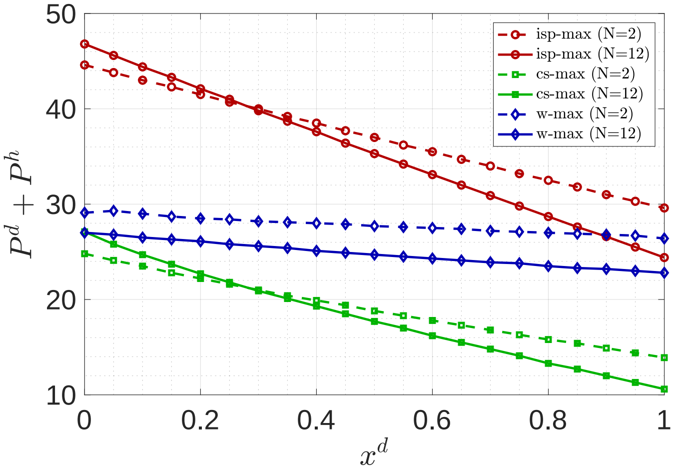


Figure 8.4: Effect of localization and number of IXPs on $P^d + P^h$

for the SVOD provider (C^{svod}) decreases as the number of interconnection points increases. This decrease in cost raises both the profit and willingness to pay of the SVOD provider. As a result, with a low level of localization, $P^d + P^h$ increases as the number of interconnection points rises. In contrast, with a high level of localization, the cost of the SVOD provider (C^{svod}) increases as the number of interconnection points rises. This leads to a decrease in both the profit and willingness to pay of the SVOD provider. Therefore, for a high level of localization, $P^d + P^h$ declines as the number of interconnection points increases.

The bundle price that maximizes aggregate consumer surplus ($P^d_{CS_{reg}} + P^h_{CS_{reg}}$) decreases nearly linearly from \$27.00 to \$10.60 (for $N = 12$) as x^d increases from 0 to 1. If a regulator were to set the bundle price to maximize social welfare, then $P^d_{W_{reg}} + P^h_{W_{reg}}$ similarly decreases from \$27.00 to \$22.80 (for $N = 12$) as x^d increases from 0 to 1. This closely tracks $P^d_{CS_{reg}} + P^h_{CS_{reg}}$, with the difference diminishing at lower x^d. The bundle prices that maximize ISP profit, $P^d_{ISP} + P^h_{ISP}$, also decreases nearly linearly with the x^d, from \$47.00 to \$24.40 (for $N = 12$) as x^d increases from 0 to 1.

Not only do N and x^d directly affect $P^d + P^h$, they also indirectly affect all prices and demands. The effect on consumers is qualitatively similar, but different in magnitude. Moving forward, we will concentrate on the regulatory approach that selects bundle prices to maximize consumer surplus, with the number of interconnection points set at $N = 12$.

When $x^d = 0$, limited premium tier subscribers would pay $P^b + P^p = \$83.66$ at the ISP chosen bundle price ($P^d_{ISP} + P^h_{ISP} = \$47.00$) but $P^b + P^p = \$85.97$ if the regulator sets the bundle price to maximize consumer surplus ($P^d_{CS_{reg}} + P^h_{CS_{reg}} = \$27.00$), and unlimited premium tier subscribers with video streaming would pay $P^b + P^p + P^v = \$180.46$ (to the ISP and all SVODs) at the ISP chosen bundle price but $P^b + P^p + P^v = \$163.07$ (to the ISP and all SVODs) at the regulator chosen bundle price. Thus, regulation of the bundle price results in the limited premium tier subscribers paying \$2.31 more and in unlimited premium tier subscribers with video streaming paying \$17.39 less; however the regulated bundle price also increases demand for the unlimited premium tier and video streaming from 2% to 20%.

When $x^d = 1$, the limited premium tier subscribers would pay \$85.32 at the ISP chosen bundle price ($P^d_{ISP} + P^h_{ISP} = \$24.40$) but \$91.41 at the regulator chosen bundle price ($P^d_{CS_{reg}} + P^h_{CS_{reg}} = \$10.60$), and the unlimited premium tier subscribers with video streaming would pay \$159.72 (to the ISP and all SVODs) at the ISP chosen bundle price but \$152.00 (to the ISP and all SVODs) at the regulator chosen bundle price. Thus, regulation of the bundle price results in the limited premium tier subscribers paying \$6.09 more and in the unlimited premium tier subscribers with video streaming paying \$7.72 less; however the regulated bundle price also increases demand for the unlimited premium tier and video streaming from 25% to 51%.

Thus far, our discussion has centered on regulatory oversight of the bundle price $P^d + P^h$. We now shift our focus to a scenario where the regulator aims to separately regulate the peering price and the unlimited usage add-on fee. Various strategies exist for splitting the bundle price between SVOD providers and unlimited premium tier customers. Our focus will shift to examining cost-sharing mechanisms as a means to equitably distribute the overall charges between the involved parties.

Recall that C^v is the incremental ISP cost per SVOD subscriber, which consists of the sum of ISP backbone costs related to SVOD traffic (C^d) and middle-mile and access network costs related to SVOD traffic (C^h). We must address whether an ISP should recover C^v across different parts of its network solely from its subscribers or also from SVOD providers.

Economists debate how to divide costs in this two-sided market, but generally agree that subscribers should cover access and middle-mile network costs. There are several rationales for this approach. First, regulatory cost accounting often dictates that access network costs be recovered from subscribers. Second, the conditions under which two networks peer affect ISPs' backbone transportation costs. However, these same conditions do not affect ISPs' middle-mile or access network transportation costs, since an ISP must carry traffic across these portions of its network regardless. On this basis, we propose that customers bear middle-mile and access network costs related to SVOD traffic (C^h), and that SVOD providers bear ISP backbone costs related to SVOD traffic (C^d).

In this approach, the regulator determines the peering price using a cost-sharing formula:

$$\frac{P^d}{P^d + P^h} = \frac{C^d}{C^d + C^h}. \tag{8.31}$$

Figure 8.5 illustrates the impact that the degree of traffic localization has on the peering price and the unlimited usage add-on price, given $N = 12$ interconnection points. According to this pricing scheme, the peering price decreases as the SVOD providers increase the localization of their content, bearing the majority of costs by routing video traffic through the nearest interconnection points to the customer. In the instance where $x = 1$, the ISP incurs no backbone transportation costs, justifying a settlement-free peering arrangement. Consistent with our expectations, the peering price that maximizes consumer surplus is significantly lower than the peering price that maximizes ISP profit.

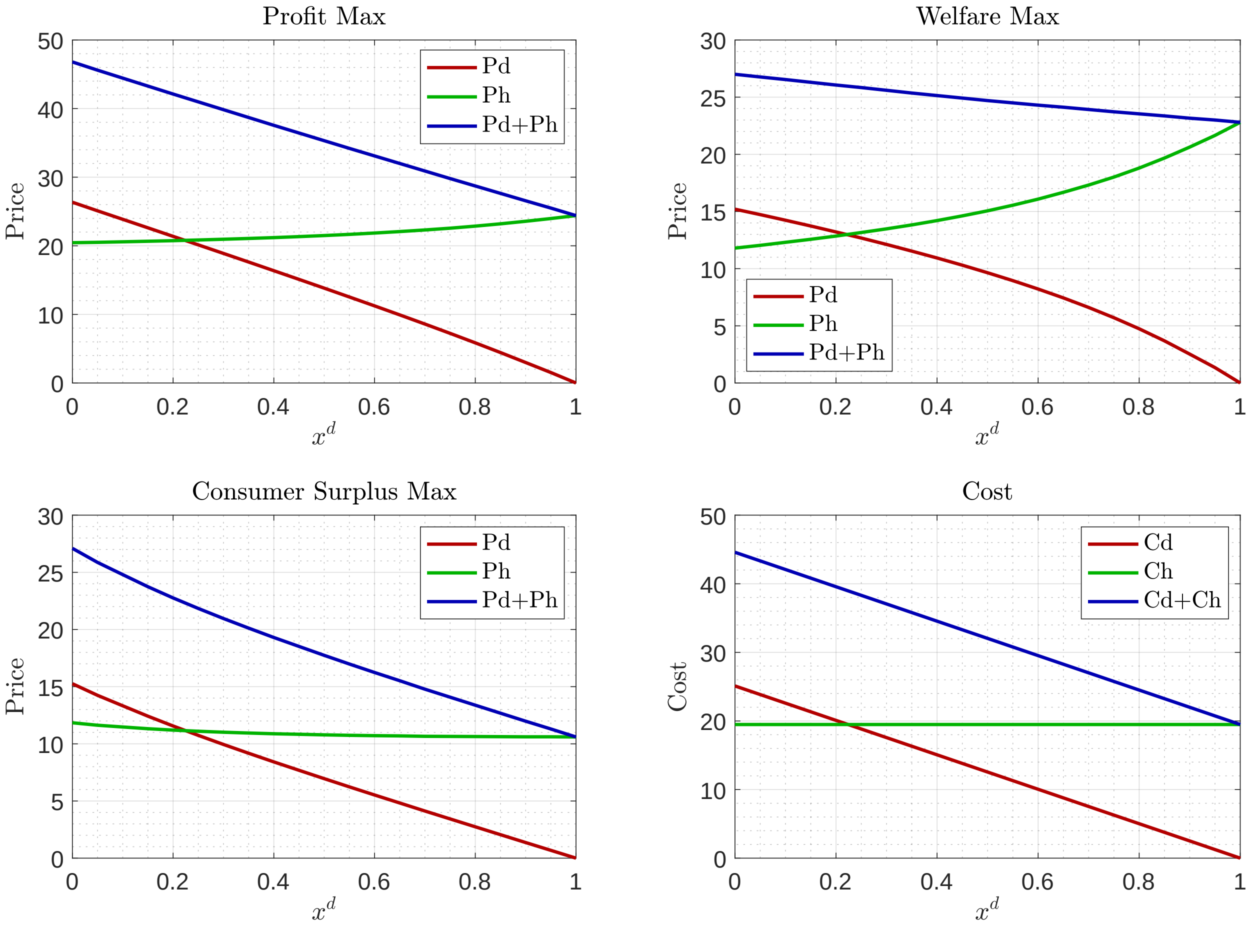


Figure 8.5: Effect of localization and number of IXPs on $P^d + P^h$

Chapter 9

Policy Proposals to FCC

The content of this section is derived from our "Comments in the Matter of Safeguarding and Securing The Open Internet, WC Docket No. 23-320," submitted to the Federal Communications Commission (FCC) on December 14, 2023 [105].

We propose that traffic exchange arrangements should be settlement-free if the interconnecting party agrees to reasonably localize the exchanged traffic.

The Federal Communications Commission's (FCC) adopted a Notice of Proposed Rulemaking (NPRM), Safeguarding and Securing the Open Internet [5], that seeks comment on whether to take the same approach to Internet traffic exchange agreements as in the 2015 Open Internet Order. Under that approach, the Commission will monitor Internet traffic exchange arrangements, provide oversight by hearing disputes about traffic exchange raised under sections 201 and 202 on a case-by-case basis, and intervene to ensure that traffic exchange arrangements are not harming or threatening to harm the open nature of the Internet [106].

The sections 201 and 202 prohibitions against unreasonable and unreasonably discriminatory practices remain the correct approach to oversight over Internet traffic exchange practices.

In 2015, the Commission stated that it lacked "the background in practices addressing Internet traffic exchange" and that it was "premature to draw policy conclusions concerning new paid Internet traffic exchange arrangements between broadband Internet access service providers and edge providers [and] CDNs" [106].

In the eight years since then, we have gained the necessary background to draw policy conclusions.

9.1 Paid Peering Is Not Likely To Result In Lower Prices Paid By Consumers

One of the policy questions in 2015 was whether paid peering would result in lower broadband prices. Large ISPs asserted that "if the broadband Internet access service provider absorbs these interconnection and transport costs, all of the broadband provider's subscribers will see their bills rise" [106]. Content providers and transit providers disagreed.

We now know that paid peering results in higher (not lower) prices paid by consumers.

First, paid peering results in an increase in the prices that consumers pay for applications and services from content providers that pay these peering fees, since the content providers will pass through a substantial portion of these peering fees to their subscribers. Such edge provider applications and services include paid video streaming services. Increased edge provider prices result in lower demand for these edge provider applications and services, including for paid video streaming services.

Second, paid peering is likely to incentivize an ISP to lower the prices it charges for its higher-priced broadband plans. These higher-priced broadband plans are utilized by most of its customers who also subscribe to paid video streaming services. By lowering the prices it charges for its higher-priced broadband plans, an ISP incentivizes subscribers to upgrade from lower-priced broadband plans to higher-priced broadband plans. However, critically, the amount of this decrease in broadband prices will be less than the paid peering fees that the broadband provider charges to content providers. In other words, an ISP will pass through only a portion of its paid peering revenue to its subscribers.

Third, paid peering is unlikely to result in lower broadband prices for its lower-priced broadband plans. Decreased prices of its higher-priced broadband plans are more than offset by paid peering fees. In contrast, an ISP would not similarly recoup lost revenue if it decreased the prices of its lower-priced broadband plans, since relatively few of these customers subscribe to paid video streaming services which generate paid peering fees.

Content providers and transit providers often cast paid peering fees as a toll that increases the profit of ISPs [106]. In contrast, large ISPs also often asserted that paid peering revenue is reinvested into network capacity and is not used to increase their profit [106].

We now know that paid peering results in higher profits of ISPs. The revenue gained by paid peering fees exceeds any decrease in broadband prices. In addition, the net revenue exceeds the cost of the incremental capacity required to transport the traffic from these content providers and transit providers. That said, the percentage increase in the profits of ISPs is relatively small. The larger effect of paid peering is a substantial percentage decrease in the profits of content providers.

9.2 The paid peering Fees That A Broadband Provider Charges Are Likely To Reduce Consumer Surplus

Another one of the policy questions in 2015 was whether paid peering is good or bad for consumers. Content providers and transit providers asserted the paid peering harms consumers. Large ISPs asserted that paid peering benefits consumers [106].

We now know that paid peering fees that an ISP charges harms consumers.

For consumers who subscribe to the higher-priced broadband plans and to paid video streaming services, paid peering results in lower broadband prices but higher video streaming prices. Critically, the amount of the decrease in broadband prices is less than the amount of the increase in video streaming prices. Thus, consumers will pay a higher total for broadband and video streaming. In addition, some lower-income consumers discontinue broadband service due to higher video streaming prices. This reduction in broadband subscription harms these lower-income consumers. For consumers who subscribe to the lower-priced broadband plans, paid peering does not significantly affect broadband prices.

For consumers who subscribe to the higher-priced broadband plans but do not subscribe to paid video streaming services, paid peering results in lower broadband prices, and thus these consumers benefit. However, the amount of this benefit is more than offset by the decrease in the benefit to other consumers.

Consumer benefit is often gauged by the traditional economic measure of consumer surplus. We now know that the peering fee that maximizes consumer surplus is lower than the peering fee that a large broadband provider will charge.

9.3 If A Content Provider Provides Sufficient Localized Traffic, An ISP Incurs The Same Cost As It Does When It Agrees To Settlement-Free Peering With Another ISP

Another one of the policy questions in 2015 was whether an ISP uses paid peering to recover the incremental costs of carrying edge provider traffic.

Large ISPs asserted that "edge providers such as Netflix are imposing a cost on broadband Internet access service providers who must constantly upgrade infrastructure to keep up with the demand" and that "when an edge provider sends extremely large volumes of traffic to a broadband Internet access service provider— e.g., through a CDN or a third-party transit service provider—the broadband provider must invest in additional interconnection capacity (e.g., new routers or ports on existing routers) and middle-mile transport capacity in order to accommodate that traffic, exclusive of 'last-mile' costs from the broadband Internet access provider's central offices, head ends, or cell sites to end-user locations" [106].

In contrast, content providers and transit providers argued that "the costs of adding interconnection capacity or directly connecting with edge providers are de minimis" [106].

We now know that an ISP incurs the same cost when it peers with a content provider or transit provider as it does when it agrees to settlement-free peering with another broadband provider, if the exchanged traffic is sufficiently localized.

9.3.1 Settlement-Free Peering Between Two ISPs Typically Requires a Minimum Number of Interconnection Points and a Maximum Traffic Ratio

We start with a review of the typical requirements for settlement-free peering between two ISPs.

Large ISPs often require other ISPs who wish to have settlement-free peering to interconnect at a specified number of interconnection points. For Comcast, Charter, AT&T, and Verizon, this minimum is between 4 and 8. This requirement is rational. As the number of interconnection points at which two ISPs peer increases, the cost to each broadband provider initially decreases. The decrease in cost is a direct result of the lower distances that each broadband provider must carry traffic across its backbone. However, there is no significant additional reduction in cost by interconnecting at more than 8 interconnection points.

In addition to requiring interconnection at a minimum number of interconnection points, large ISPs often specify a list of eligible interconnection points that this minimum must be chosen from. This requirement is also rational. The cost to each broadband provider is minimized by selecting interconnection points that span the country, so that the average distances the broadband provider carries traffic across its backbone are relatively small.

However, notably, these requirements about the minimum number of interconnection points and their locations are all about reducing the cost of carrying traffic across an ISP's backbone. There is no change in the cost of carrying traffic across an ISP's access or middle-mile networks, since the access and middle-mile networks lay in between the major interconnection points and the subscribers.

Finally, large ISPs often require other ISPs who wish to have settlement-free peering to ensure that the ratio of incoming traffic to outgoing traffic remains below approximately

2:1. This requirement is also rational when the interconnection is between two ISPs. The cost to each broadband provider decreases as the number of interconnection points increase when the traffic ratio is below 2:1. At higher traffic ratios, there is no benefit to an ISP from interconnecting at multiple interconnection points. However, as discussed below, such a traffic ratio requirement is not rational when the interconnection is between an ISP and a content provider.

9.3.2 Settlement-Free Peering Between an ISP and a Content Provider Should Require Sufficient Localization of Traffic

Large ISPs argued that content providers (including CDNs) and transit providers should meet the same requirements for settlement-free peering as do other ISPs. They contend that "if the other party is only sending traffic, it is not contributing something of value to the broadband Internet access service provider."[106] In contrast, content providers and transit providers assert that traffic ratios requirements "are arbitrarily set and enforced and are not reflective of how [ISPs] sell broadband connections and how consumers use them".[106] They also assert that content providers and transit providers "are covering the costs of carrying this traffic through the network, bringing it to the gateway of the Internet access service, unlike in the past where both parties covered their own costs to reach the Tier 1 backbones where traffic would then be exchanged on a settlement-free basis."[106]

These two stakeholders are talking past one another. The ISPs are focusing on traffic volume, while the content providers and transit providers are focusing on the locations at which traffic is exchanged.

When traffic is exchanged between two ISPs, the cost to each broadband provider is principally a function of traffic volume since each broadband provider carries the exchanged traffic across its backbone network. However, when traffic is exchanged between an ISP and a content provider or transit provider, the cost to the broadband provider is principally a function of the routing of exchanged traffic, which determines whether the broadband provider needs to carry this exchanged traffic across its backbone network.

The routing is determined by two factors: the locations of interconnection points and the locations of the end users. Content providers localize a portion of their traffic by placing content servers at multiple interconnection points and choosing the server that is closest to the end user. Transit providers may localize a portion of their traffic by handing off this traffic at an interconnection point that is relatively close to the end user. When a content provider or transit provider localizes a portion of exchanged traffic, it reduces an ISP's costs by reducing the distance that it must carry traffic across its backbone network.

The amount of this reduction in an ISP's costs is determined by the amount of localization. This is in turn determined by: (1) the number of interconnection points, (2) the location of these interconnection points, and (3) the proportion of traffic that is exchanged at an interconnection point that is relatively close to the end user.

If a content provider or transit provider provides sufficient localization of exchanged traffic, an ISP incurs the same cost as it does when it agrees to settlement-free peering with another broadband provider. On one hand, the broadband provider does not benefit from exchanging outgoing traffic with a content provider, as it does with another broadband provider. On the other hand, the broadband provider's costs are reduced by the localization of traffic, which it does not achieve when exchanging traffic with another broadband Internet service provider. If there is sufficient localization of traffic, then the net cost to the broadband provider is unchanged.

Our conclusion is that settlement-free peering is warranted if a content provider or transit provider provides sufficient localization of exchanged traffic. Traffic is sufficiently localized if: (1) they interconnect at a reasonable number of interconnection points, (2) the locations of these interconnection points span the country, and (3) the proportion of traffic that is exchanged at an interconnection point that is relatively close to the end user is sufficiently high. However, if the exchanged traffic is not sufficiently localized, then settlement-free peering is not warranted.

9.3.3 Settlement-Free Peering Between an ISP and a Content Provider Should Not Depend on the Traffic Ratio

There is no rationale reason for settlement-free peering between an ISP and a content provider to require adherence to a traffic ratio. When two ISPs interconnect, the value to each broadband provider is a function of the ratio of incoming traffic to outgoing traffic. This is because each broadband provider transports incoming traffic across its backbone network. In contrast, when an ISP interconnects with a content provider or transit provider that localizes a sufficient portion of its traffic, the value to the broadband provider stems from the localization of the traffic. The localization reduces the cost to the broadband provider, since it reduces its need to carry the traffic across its backbone network. The traffic ratio is now irrelevant.

9.4 The Public Interest Is Best Served by Peering Prices That Are Lower Than Those Likely Charged by Large ISPs

Another one of the policy questions in 2015 was whether any peering price upon which an ISP and a content provider or transit provider agree is equally in the public interest. Large ISPs often implied that any commercially negotiated arrangement reflects the public interest

[106]. In contrast, content providers and transit providers often implied that even when they agreed to paid peering, the agreement was forced and not in the public interest [106].

We now know that not all commercially negotiated peering prices are in the public interest.

If an ISP were to set peering prices to recover the backbone network costs associated with carrying a content provider's or transit provider's traffic, the resulting peering price would depend on the number of interconnection points at which they peer and the proportion of traffic that is localized. For example, in the case of peering between an ISP and a content provider, settlement-free peering is warranted by costs when they interconnect at a minimum of 6 interconnection points and localize at least 50% of the traffic.

However, when an ISP sets peering prices to maximize its profit, the resulting peering price no longer primarily depends on its costs. Now, the resulting peering price primarily depends on a content provider's willingness-to-pay for peering. This commercially negotiated peering price is almost never settlement-free. For example, in the case of peering between broadband provider and a content provider, the broadband provider is likely to charge a positive peering fee whenever traffic localization is less than 90%.

Consumers are not ambivalent about whether peering prices are cost-based or profit-maximizing. Consumer surplus is maximized when peering prices are substantially lower than those that maximize an ISP's profit.

9.5 The Commission Should Require an ISP to Offer Settlement-Free Peering to Content Providers That Agree to Reasonably Localize the Exchanged Traffic

The 2023 NPRM proposes to decline to apply any Open Internet rules to Internet traffic exchange and instead to “watch, learn, and act as required” [5].

The “watch, learn, and act” approach taken in 2015 was justified based on the Commission’s lack of background in 2015 about practices addressing Internet traffic exchange [106]. In the eight years since then, we have gained the necessary background to draw policy conclusions. It is time to act upon this new knowledge.

The 2015 Open Internet Order considered and declined to apply the bright line rules or the general conduct standard to Internet traffic exchange arrangements. While applying those rules to Internet traffic exchange arrangements could, if done properly, address what we have learned in the last eight years, there is a simpler approach.

The Commission should continue to monitor Internet traffic exchange arrangements under sections 201 and 202. In addition, however, it is now time for the Commission to determine that certain types of Internet traffic exchange arrangements are unreasonable or unreasonably discriminatory practices and would violate sections 201 or 202.

We now know that paid peering is not likely to result in lower prices paid by consumers. We also now know that the paid peering fees that an ISP charges are likely to reduce consumer surplus, and are thus not generally in the public interest. We also now know that if a content provider or transit provider provides sufficient localization of exchanged traffic, an ISP incurs the same cost as it does when it agrees to settlement-free peering with another broadband provider. Finally, we now know that the public interest is best served by peering prices that are lower than those likely charged by large ISPs.

Settlement-free peering is warranted if a content provider or transit provider provides sufficient localization of exchanged traffic. Traffic is sufficiently localized if: (1) they interconnect at a reasonable number of interconnection points, (2) the locations of these interconnection points span the country, and (3) the proportion of traffic that is exchanged at an interconnection point that is relatively close to the end user is sufficiently high. In particular, our analysis shows that in the case of peering between an ISP and a content provider, settlement-free peering is warranted when they interconnect at a minimum of 6 interconnection points and localize at least 50% of the traffic. The Commission should require an ISP to offer settlement-free peering to content providers and transit providers that agree to reasonably localize the exchanged traffic.

Chapter 10

Conclusion

10.1 Summary

Debates over paid peering and usage fees have expanded from the United States to Europe and South Korea. ISPs and content providers disagree about the effect of paid peering on broadband prices. ISPs assert that the revenue they generate from paid peering fees is used to lower broadband prices, whereas content providers assert that paid peering fees increase ISP profit but do not affect broadband prices.

Our objective here was to understand an ISP's cost for directly peering with a content provider and the peering fee that maximizes an ISP's profit. The range from the cost-based peering fee to the profit-maximizing peering fee determines possible peering fees that the parties may agree to, if unregulated. The lower boundary is shaped by costs, while the upper limit is dictated by profit maximization. The upper limit of this range is the intersection of two components: the peering price that maximizes the ISP's profit, and the content provider's maximum willingness to pay.

In this dissertation, we derived the cost-based peering fee between two ISPs, the cost-based peering fee between a transit provider and an ISP which agree to peer with each other, the cost-based peering fee between a content provider and an ISP which directly interconnect with each other, and the ISP's profit-maximizing peering fee between a content provider and an ISP which directly interconnect with each other. We analyzed the impact of routing policies, traffic ratios, and traffic localization on peering fee. Our analysis showed that these factors play a crucial role in determining the profit-maximizing and the cost-based fees for peering.

We developed two cost models. The first model is an analytical model in which an ISP serves the contiguous United States with a uniformly distributed population of subscribers. The ISP's network consists of access networks, middle mile networks, and a backbone, each with a regular geometry. The second model is a numerical model in which subscribers are distributed according to census statistics. Access networks are based on counties, and interconnection points are chosen from a list of the largest exchanges in the United States. Traffic matrices are based on population, and traffic-sensitive costs are modeled as a function of both distance and traffic volume. We determined the distances on each portion of an ISP's network over which it carries traffic to and from an end user. We calculated the average distance using traffic matrices. We modeled the average traffic-sensitive cost associated with carrying the traffic over these average distances.

The focus of the next part of this dissertation is to relate the settlement-free peering requirements of large Internet Service Providers (ISPs) to the value the arrangement brings to the ISP. We represented value in terms of an ISP's traffic-sensitive costs. We also investigated whether it is rational to apply these settlement-free peering requirements to the interconnection between an ISP and a content provider.

In order to explain the common settlement-free peering requirements of the largest ISPs in the United States, we examined the effect of the number of interconnection points at which two networks peer, the locations of these interconnection points, traffic ratios, and symmetric routing on an ISP's variable traffic-sensitive costs.

Our results show that symmetric ISPs would likely reach a settlement-free peering agreement. When two ISPs peer with a traffic ratio of 1:1, the variable traffic-sensitive cost is uni-modal, and we estimated that it is minimized with 8 IXPs. There may be little value in requiring interconnection at more than 6 IXPs. The ISP's cost is typically minimized by selecting interconnection points that span the country and are near population centers. However, peering between ISPs with unequal traffic may require payment between the two networks, and the payment depends on the traffic ratio. When two ISPs using hot potato routing peer with an imbalanced traffic ratio that is below 2:1, the decrease in the upstream cost with the number of IXPs dominates the corresponding increase in the downstream cost, and thus interconnecting at 6 to 8 IXPs results in close to a minimum total cost. Requiring interconnection at more than 8 interconnection points is of little incremental value. In contrast, when the traffic ratio is above 2:1, the variation in the downstream cost with the number of IXPs dominates. As a result, the total cost increases with the number of IXPs, and thus it is no longer rational for the ISP to agree to settlement-free peering.

In the next part of this dissertation, we turned to peering between a transit provider and an ISP. We examined how routing policies, traffic ratios, and traffic localization impact backbone costs for the ISP and the transit provider. We found that video traffic localization impacts ISP and transit provider backbone costs differently, with increasing video localization by the transit provider leading to decreased ISP cost but increased transit provider cost. Increasing volumes of video traffic increases costs for both, with the impact more pronounced for an ISP when traffic localization is low and for a transit provider when it's high. The ratio of non-video downstream to upstream traffic also affects an ISP's cost share; as the ratio of non-video downstream traffic to upstream traffic increases, an ISP's cost share increases.

We then examined the cost-based peering fee between a transit provider and an ISP. We defined *cost-based* as the peering fee that equalized the net backbone costs of the transit provider and the ISP. We found that the cost-based peering fee for a transit provider using hot potato routing depends on the downstream-upstream traffic ratio, while for a transit provider using cold potato routing for video traffic, it depends on the proportion of localized video traffic, the non-video traffic ratio, and the volume of video traffic. The cost-based peering fee increases with the non-video traffic ratio and decreases with the proportion of localized video traffic. It also decreases more rapidly with the proportion of localized video traffic for higher volumes of video traffic. A transit provider should pay an ISP for peering if it doesn't localize a sufficient proportion of the video traffic. The cost-based peering fee may be positive and substantial if there is a high volume of video traffic with low localization.

In the next part of this dissertation, we turned to peering between a content provider and an ISP. We examined the cost-based peering fee between a content provider and an ISP which directly interconnect with each other. Here, we defined *cost-based* as the peering fee that results in the same ISP net costs for transporting the video traffic as in the case in which the video traffic is transported across a transit provider's network. We argued that an ISP should be indifferent between peering with another ISP or a transit provider and peering directly with a content provider, if the sum of the ISP's backbone transportation costs and any peering fee is unaffected.

Our results indicate that the cost-based peering fee is solely dependent on the localization of SVOD traffic and the number of interconnection points. Our results demonstrate that as the SVOD provider sends traffic with more localization, the cost-based peering fee decreases. The cost-based peering fee also varies with the number of IXPs at which they agree to peer. When localization is very low, the cost-based peering fee increases slightly with the number of interconnection points. However, for moderate to high localization, the cost-based peering fee decreases with the number of IXPs.

In the next part of this dissertation, we focused on settlement-free peering between ISPs and large content providers. When the cost-based payment is zero, we considered settlement-free peering to be a cost-based interconnection arrangement. Thus, we were particularly interested in the conditions under which settlement-free peering is cost-based. Large ISPs have often asserted that content providers should meet the same settlement-free peering requirements on the number of interconnection points and the traffic ratio as do ISPs in order to qualify for settlement-free peering. However, it is not clear the degree to which the settlement-free peering requirements between two ISPs discussed above should apply. Therefore, we analyzed settlement-free peering requirements about the number and location of interconnection points between a large content provider and an ISP.

We first considered a content provider that does not replicate its content and delivers traffic using hot potato routing. We showed that the ISP has little incentive to engage in settlement-free peering. We next considered a content provider that replicates all of its content at peering points and delivers 100% of traffic to the ISP locally. We showed that it is rational for an ISP to agree to settlement-free peering, if the content provider agrees to interconnect at a minimum of 9 IXPs. Finally, we considered a content provider that hosts a content server at peering points, but that replicates only a portion of this content on each of these servers. We showed that it is rational for an ISP to agree to settlement-free peering, if the content provider agrees to interconnect at a specified minimum number of interconnection points and to deliver a specified minimum proportion of traffic locally.

Our results indicate that an ISP should have different settlement-free peering requirements for content providers than for other ISPs. We also showed that the settlement-free peering requirements for content providers may include a specified minimum number of interconnection points and a specified minimum amount of traffic to be delivered locally. We found that as the number of interconnection points decreases, the content provider should increase the proportion of locally sent video traffic to maintain eligibility for settlement-free peering. However, we certainly expect there to be *no* traffic ratio requirements.

In the next part of this dissertation, we proposed a model of user subscription to broadband service tiers and to subscription video on demand (SVOD) services. We considered a monopoly ISP that offers a basic tier and a premium tier differentiated by download speed, both with data caps, and an add-on that allows unlimited usage. We aggregated all SVOD providers that directly interconnect with the ISP. Consumers differ in the utilities they place on broadband service tiers and on SVOD service, and each customer chooses the service which maximizes his/her surplus. Consumers decide whether to subscribe to broadband and if so to which tier, and whether to subscribe to SVOD services. We derived the demand of each broadband service tier and of SVOD services, the associated ISP profit, and aggregated SVOD providers' profit. We also showed the effect of SVOD traffic localization and the number of interconnection points on the monthly marginal costs of the ISP and SVOD providers.

We then developed a two-sided model in which a profit-maximizing ISP determines broadband prices and the peering price and in which video streaming providers choose their price based on the peering price. Numerical parameters were chosen based on public information about broadband and video streaming prices and subscription. We proved that a profit-maximizing ISP's chosen broadband and peering prices satisfy a generalization of the well-known Lerner rule, which specifies how these prices are related to a matrix of elasticities and cross-elasticities of demand.

In the next part of this dissertation, we determined the peering fee that maximizes an ISP's profit. The results indicate that a profit-maximizing ISP may charge SVOD providers the highest amount their willingness to pay permits. Our research reveals that as SVOD traffic localization increases, the peering price that ISPs can demand decreases due to a reduced maximum amount that SVOD providers are willing to pay for peering. Also, our results demonstrate with a low level of localization, the peering fee charged by the profit-maximizing ISP increases as the number of interconnection points rises. However, for a high level of localization, the peering fee charged by the profit-maximizing ISP declines as the number of interconnection points increases.

So far, we determined an ISP's cost for directly peering with a content provider. Such a cost-based peering price may be the minimum price an ISP will accept. We also identified the peering price that maximizes an ISP's profit using a two-sided market model. Unregulated, these prices establish a range from the cost-based peering price to the profit-maximizing peering price. We found that the profit-maximizing peering fee generally surpasses the cost-based fee, and this gap may diminish with increasing traffic localization. Regulatory oversight of peering prices may be warranted when there is a substantial difference between cost-based and profit-maximizing prices. In particular, we determined the effect of content localization and the number of interconnection points on this range of peering prices. Finally, we delved into a critical analysis of how regulatory oversight of the peering price and the unlimited usage add-on price could influence consumer surplus and societal welfare. By comparing an unregulated approach (e.g., ISP profit maximization) with regulatory approaches (e.g., maximizing consumer surplus or social welfare), we gained an understanding of the potential outcomes of such regulatory interventions.

In the next part of this dissertation, we examined the potential implications of regulatory oversight on peering prices and unlimited usage add-on fees. We used the term "bundle price" to refer to the combined total of the peering fee and the unlimited usage add-on price. We considered a regulator that wishes to determine the bundle price that maximizes either consumer surplus or social welfare, while the ISP, with its profit-maximizing objectives, determines the pricing for the basic and premium tiers. We showed that consumer surplus is a unimodal function of the bundle price, and when a regulator sets the bundle price to maximize consumer surplus, it chooses a lower bundle price than does the ISP. As a result, SVOD prices drop to reflect the lower SVOD costs. However, the ISP then increases the price of the limited premium tier, recouping most of its loss from the lower peering price and unlimited usage add-on fee and regaining some of the increased consumer surplus from lower SVOD prices. We also showed the effect of the number of interconnection points and the degree of content localization by SVOD services on the bundle prices that maximize ISP profit, social welfare, and consumer surplus.

Finally, we re-examined the arguments put forth by large ISPs and large content providers. ISPs and content providers disagree about the effect of paid peering on consumer surplus, and ultimately about whether peering prices should be regulated. ISPs assert that paid peering increases consumer surplus because it eliminates an inherent subsidy of consumers with high video streaming use by consumers without, whereas content providers assert that paid peering decreases consumer surplus because paid peering fees are passed onto consumers through higher video streaming prices and because there is no corresponding reduction in broadband prices. As a result, ISPs argue that the market should determine peering prices, while content providers argue that they should be entitled to settlement-free peering if they interconnect with the ISP close enough to consumers.

Our results show that the claims of the ISPs and of the content providers are both incorrect. We reject ISP assertions that they should apply the same settlement-free peering requirements to both peering ISPs and peering content providers. We also reject ISP assertions that they should be compensated by large content providers regardless of the amount of video content localization. We also reject any assertions by transit providers or content providers that should be entitled to settlement-free peering solely because the ISP's customers have already paid the ISP to transport the traffic the content providers are sending.

We now know that paid peering is not likely to result in lower prices paid by consumers. We also now know that the paid peering fees that an ISP charges are likely to reduce consumer surplus, and are thus not generally in the public interest. We also now know that if a content provider or transit provider provides sufficient localization of exchanged traffic, an ISP incurs the same cost as it does when it agrees to settlement-free peering with another broadband provider. Finally, we now know that the public interest is best served by peering prices that are lower than those likely charged by large ISPs.

Settlement-free peering is warranted if a content provider or transit provider provides sufficient localization of exchanged traffic. Traffic is sufficiently localized if: (1) they interconnect at a reasonable number of interconnection points, (2) the locations of these interconnection points span the country, and (3) the proportion of traffic that is exchanged at an interconnection point that is relatively close to the end user is sufficiently high. In particular, our analysis shows that in the case of peering between an ISP and a content provider, settlement-free peering is warranted when they interconnect at a minimum of 6 interconnection points and localize at least 50% of the traffic. Therefore, we propose that the Federal Communications Commission (FCC) should require an ISP to offer settlement-free peering to content providers and transit providers that agree to reasonably localize the exchanged traffic.

10.2 Future Research

There are several promising areas for future work that can build upon the analysis presented here:

- Investigate interconnection dynamics in the presence of multiple ISPs competing for subscribers. The models in this dissertation focus on a monopoly ISP, but expanding the analysis to oligopoly market structures would provide additional insights.
- Incorporate content provider competition into the model. This dissertation aggregated content providers into a single entity. Exploring competition among content providers could reveal new strategic behaviors in response to peering fees.
- Incorporate quality of experience factors more explicitly into the modeling, such as the impact of interconnection polices on video latency, rebuffering rates, and video quality.

These technical factors affect consumer demand and willingness to pay, so capturing them may alter the economic analysis.

- Incorporate quality of service into the cost model. Adding quality of service factors could better capture the full costs incurred by ISPs and content providers. This could reveal new insights into cost-based peering fees.
- Analyze the effects of an ISP owning a content provider. Some ISPs have acquired content providers. Modeling this vertical integration could reveal impacts on pricing power and consumer welfare. An ISP may price discriminate in favor of its own content, changing market dynamics.
- Expand the model with additional consumer heterogeneity factors. The model currently accounts for heterogeneity in preferences for broadband tiers and content. Adding other sources of heterogeneity like income could enhance insights into consumer surplus.
- Extending the analysis to other geographic markets. This dissertation has focused on the US market, but the models could be adapted to examine peering in the context of other countries. How do factors like population density, competitive dynamics, and regulatory approaches affect peering arrangements globally?
- New architectures for content distribution and traffic localization could affect costs and incentives in significant ways.
- Examine the interplay between paid peering and network neutrality regulations. How would rules prohibiting ISPs from charging content providers for priority delivery over "best effort" service impact peering arrangements and fees?
- Conduct empirical analysis of real-world interconnection agreements and disputes to validate the theoretical predictions from the models developed here. Access to detailed commercial data could strengthen the practical relevance of the economic frameworks.

Pursuing these directions would provide fuller understanding of Internet interconnection agreement. The work in this dissertation establishes a foundation, and future research can build upon it to address evolving technical and business realities in this critical part of the Internet ecosystem. There remain many open questions surrounding the economics of interconnection that warrant deeper investigation.

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Appendix A

Proof of Theorem 3.1

In (11), we have

$$\begin{aligned} &ED^{b,hot}_{1,down} = \\ &\sum_{g \in I_1} \sum_{g' \in I_1} D^b_1(g, g') P(IXP^{p,hot}_{1,down} = g) P(IXP^u_1 = g'). \end{aligned} \tag{A.1}$$

The distance $D^b_1(g, g')$ is given by (9). The probability distribution of $IXP^{p,hot}_{1,down}$ is given in (7), and the probability distribution of IXP^u is similarly uniformly distributed. Substituting these expressions into (A.1),

$$\begin{aligned} ED^{b,hot}_{1,down} &= \sum_{i^g \in l^N_1} \sum_{i^{g'} \in l^N_1} \frac{L}{N} |i^g - i^{g'}| \frac{1}{N} \frac{1}{N} \\ &= \frac{1}{N^2} \sum_{i^g \in l^N_1} \sum_{i^{g'} \in l^N_1} \frac{L}{N} |i^g - i^{g'}|. \end{aligned} \tag{A.2}$$

The inner sum is the average distance from interconnection point i^g to other interconnection points. If i^g is the k^{th} interconnection point (from left to right), then the inner sum

$$
\begin{aligned}
&\sum_{i^{g'} \in l_1^N} \frac{L}{N} |i^g - i^{g'}| \\
&= \frac{L}{N} \{ [|1-k| + ... + |-1|] + 0 + [|1| + ... + |N-k|] \} \\
&= \frac{L}{N} \left[\frac{k(k-1)}{2} + \frac{(N-k)(N-k+1)}{2} \right].
\end{aligned}
\tag{A.3}
$$

Substituting (A.3) into (A.2),

$$
\begin{aligned}
&ED_{1,down}^{b,hot} = \frac{1}{N^2} \sum_{k=1}^{N} \frac{L}{N} \left[\frac{k(k-1)}{2} + \frac{(N-k)(N-k+1)}{2} \right] \\
&= \frac{L}{N^3} \left[\frac{1}{2}(N+1)N^2 + \sum_{k=1}^{N} k^2 - (N+1) \sum_{k=1}^{N} k \right] \\
&= \frac{L}{N^3} \left[\frac{1}{2}(N+1)N^2 + \frac{N(N+1)(2N+1)}{6} - \frac{N(N+1)^2}{2} \right] \\
&= \frac{L(N-1)(N+1)}{3N^2}.
\end{aligned}
\tag{A.4}
$$

Appendix B

Proof of Theorem 3.2

In (14), we have:

$$ED_1^m = \sum_{g' \in I_1} \sum_{A_1(j,k) \subset R_1(g')} D_1^m(g', A_1(j,k)) P_1(j,k). \tag{B.1}$$

The access networks $A_1(j,k) \subset R_1(g')$ are given by

$$\begin{aligned} \frac{(i^{g'}-1)L}{aN} + 1 \leq & j \leq \frac{i^{g'}L}{aN} \\ 1 \leq & k \leq \frac{W}{b} \end{aligned} \tag{B.2}$$

The double sum in (B.1) can thus be written as

$$ED_1^m = \sum_{i^{g'}=1}^{N} \sum_{k=1}^{\frac{W}{b}} \sum_{j=\frac{(i^{g'}-1)L}{aN}+1}^{\frac{i^{g'}L}{aN}} D_1^m(g', A_1(j,k)) P_1(j,k). \tag{B.3}$$

The distance $D_1^m(g', A_1(j,k))$ is given by (10):

$$D_1^m(g', A_1(j,k)) = \sqrt{\left(\frac{(2j-1)a - L/N(2i^{g'}-1)}{2}\right)^2 + \left(\frac{(2k-1)b - W}{2}\right)^2} \tag{B.4}$$

The variable substitution $j' = j - \frac{(i^{g'}-1)L}{aN}$ will help simplify the equation:

$$D_1^m = \sqrt{\left(\frac{(2j'-1)a - L/N}{2}\right)^2 + \left(\frac{(2k-1)b - W}{2}\right)^2} \tag{B.5}$$

Changing the inner sum over j into a sum over j' and substituting $P_1(j,k) = ab/LW$,

$$ED_1^m = \frac{ab}{LW} \sum_{i^{g'}=1}^{N} \sum_{k=1}^{\frac{W}{b}} \sum_{j'=1}^{\frac{L}{aN}} D_1^m \tag{B.6}$$

D_1^m is no longer a function of $i^{g'}$, and thus we can remove the outer sum, resulting in

$$ED_1^m = \frac{abN}{LW} \sum_{k=1}^{\frac{W}{b}} \sum_{j'=1}^{\frac{L}{aN}} \sqrt{\left(\frac{(2j'-1)a - L/N}{2}\right)^2 + \left(\frac{(2k-1)b - W}{2}\right)^2}. \tag{B.7}$$

Appendix C

Proof of Theorem 3.3

In (16), we have

$$ED_1^a = \frac{1}{ab}\int_{-\frac{a}{2}}^{\frac{a}{2}}\int_{-\frac{b}{2}}^{\frac{b}{2}}\sqrt{x^2+y^2}\,dy\,dx. \tag{C.1}$$

By symmetry,

$$ED_1^a = \frac{4}{ab}\int_{0}^{\frac{a}{2}}\int_{0}^{\frac{b}{2}}\sqrt{x^2+y^2}\,dy\,dx. \tag{C.2}$$

We first partition the area of integration into regions below and above the 45-degree line, resulting in

$$\begin{gathered}\int_{0}^{\frac{a}{2}}\int_{0}^{\frac{b}{2}}\sqrt{x^2+y^2}\,dy\,dx = \\ \int_{0}^{\frac{b}{2}}\int_{0}^{\frac{ay}{b}}\sqrt{x^2+y^2}\,dx\,dy + \int_{0}^{\frac{a}{2}}\int_{0}^{\frac{bx}{a}}\sqrt{x^2+y^2}\,dy\,dx\end{gathered} \tag{C.3}$$

Converting the integral into polar coordinates by substituting $x = r\cos\theta$ and $y = r\sin\theta$, the previous expression can be written as

$$\begin{aligned}
&\int_0^{\tan^{-1}\frac{a}{b}}\int_0^{\frac{b}{2}\sec\theta} r^2\ dr\ d\theta + \int_0^{\tan^{-1}\frac{b}{a}}\int_0^{\frac{a}{2}\sec\theta} r^2\ dr\ d\theta \\
&= \frac{b^3}{24}\int_0^{\tan^{-1}\frac{a}{b}} \sec^3\theta\ d\theta + \frac{a^3}{24}\int_0^{\tan^{-1}\frac{b}{a}} \sec^3\theta\ d\theta \\
&= \frac{b^3}{48}\left[\frac{2a}{b^2}\sqrt{(\frac{a}{2})^2+(\frac{b}{2})^2} + \sinh^{-1}(\frac{a}{b})\right] \\
&+ \frac{a^3}{48}\left[\frac{2b}{a^2}\sqrt{(\frac{a}{2})^2+(\frac{b}{2})^2} + \sinh^{-1}(\frac{b}{a})\right] \\
&= \frac{a^3\text{sinh}^{-1}(\frac{b}{a}) + b^3\text{sinh}^{-1}(\frac{a}{b}) + 2ab\sqrt{a^2+b^2}}{48}.
\end{aligned} \tag{C.4}$$

Substituting this expression into (C.2),

$$ED_1^a = \frac{a^3\text{sinh}^{-1}(\frac{b}{a}) + b^3\text{sinh}^{-1}(\frac{a}{b}) + 2ab\sqrt{a^2+b^2}}{12ab}. \tag{C.5}$$

Appendix D

Proof of Theorem 4.1

The peering fee that equalizes net costs is given by:

$$C^{ISP^1} - P^{ISP^2,ISP^1} = C^{ISP^2} + P^{ISP^2,ISP^1}, \tag{D.1}$$

i.e.,

$$P^{ISP^2,ISP^1} = \frac{1}{2}(C^{ISP^1} - C^{ISP^2}) \tag{D.2}$$

By using equations (4.14),(4.15), and (D.2) we can express the fair peering fee in terms of traffic volumes and average backbone distances:

$$P^{ISP^2,ISP^1} = \frac{1}{2}c^b(V_d^1 - V_u^1)ED_{num,down}^{b,hot}(M), \tag{D.3}$$

or, equivalently, in terms of the traffic ratio r^1:

$$P^{ISP^2,ISP^1} = \frac{1}{2}c^bV_u^1(r^1 - 1)ED_{num,down}^{b,hot}(M) \tag{D.4}$$

Therefore, the fair peering fee between two ISPs is:

$$P^{ISP^2,ISP^1} = \frac{1}{2}c^b(V_d^1 - V_u^1)ED_{num,down}^{b,hot}(M) \tag{D.5}$$

Appendix E

Proof of Theorem 5.1

We denote the ISP's traffic-sensitive backbone cost by $C^{ISP}_{(ISP-TP,M,x)}$, and partition it into the cost of delivering downstream non-video traffic, which flows from the source S to the user U, (denoted by $C^{ISP}_{S,U,non-video}$), the cost of delivering downstream video traffic, which flows from the source S to the user U, (denoted by $C^{ISP}_{S,U,video}$), and the cost of delivering upstream traffic, which flows from the user U to the source S, (denoted by $C^{ISP}_{U,S}$):

$$C^{ISP}_{(ISP-TP,M,x)} = C^{ISP}_{S,U,non-video} + C^{ISP}_{S,U,video} + C^{ISP}_{U,S} \tag{E.1}$$

The cost of delivering downstream non-video traffic using hot potato routing is:

$$C^{ISP}_{S,U,non-video} = c^b V^{nv}_{down} ED^{b,hot}_{num,down}(M) \tag{E.2}$$

where c^b is the cost per unit distance and per unit volume in the backbone network, and $ED^{b,hot}_{num,down}(M)$ is the average distance on the ISP's backbone network of downstream non-video traffic with hot potato routing, when interconnecting at $M = 12$ IXPs.

The cost of delivering downstream video traffic is the sum of the costs of delivering localized and non-localized video traffic:

$$C^{ISP}_{S,U,video} = c^b V^v_{down} \Big[x ED^{b,cold}_{num,down}(M) + (1-x) ED^{b,hot}_{num,down}(M) \Big] \tag{E.3}$$

The first term is the ISP's backbone cost for localized video traffic, which the transit provider delivers using cold potato routing. The second term is the ISP's backbone cost for non-localized video traffic, which the transit provider delivers using hot potato routing.

The cost of delivering upstream traffic using hot potato routing is:

$$\begin{aligned} C^{ISP}_{U,S} &= c^b V_{up} ED^{b,hot}_{num,up}(M) \\ &= c^b V_{up} ED^{b,cold}_{num,down}(M), \end{aligned} \tag{E.4}$$

Using the definition of the two traffic ratios r^{nv} and r^v, and the fact that $ED^{b,cold}_{num,down}(M) = 0$, equations (E.1)-(E.4) can be simplified. The traffic-sensitive backbone cost of the ISP when peering with the transit provider is:

$$\begin{aligned} C^{ISP}_{(ISP-TP,M,x)} &= c^b \Big[V^{nv}_{down} + V^v_{down}(1-x) \Big] ED^{b,hot}_{num,down}(M) \\ &= c^b V_{up} \Big[r^{nv} + r^v (1-x) \Big] ED^{b,hot}_{num,down}(M) \end{aligned} \tag{E.5}$$

Appendix F

Proof of Theorem 5.2

We denote the transit provider's traffic-sensitive backbone cost by $C^{TP}_{(ISP-TP,M,x)}$, and partition it into the transit provider's downstream cost for delivering ISP upstream traffic, which flows from the user U to the source S, (denoted by $C^{TP}_{U,S}$), its upstream cost for delivering ISP downstream non-video traffic, which flows from the source S to the user U, (denoted by $C^{TP}_{S,U,non-video}$), and its upstream cost for delivering ISP downstream video traffic, which flows from the source S to the user U, (denoted by $C^{TP}_{S,U,video}$):

$$C^{TP}_{(ISP-TP,M,x)} = C^{TP}_{U,S} + C^{TP}_{S,U,non-video} + C^{TP}_{S,U,video} \tag{F.1}$$

The downstream cost to the transit provider for delivering ISP upstream traffic using hot potato routing is:

$$C^{TP}_{U,S} = c^b V_{up} ED^{b,hot}_{num,down}(M) \tag{F.2}$$

The upstream cost to the transit provider for delivering ISP downstream non-video traffic using hot potato routing is:

$$\begin{aligned} C^{TP}_{S,U,non-video} &= c^b V^{nv}_{down} ED^{b,hot}_{num,up}(M) \\ &= c^b V^{nv}_{down} ED^{b,cold}_{num,down}(M) \end{aligned} \tag{F.3}$$

The upstream cost to the transit provider for delivering ISP downstream video traffic is the sum of the costs of delivering localized and non-localized video traffic:

$$\begin{aligned} C^{TP}_{S,U,video} &= c^b V^{v}_{down} \left[x ED^{cold}_{up}(M) + (1-x) ED^{b,hot}_{num,up}(M) \right] \\ &= c^b V^{v}_{down} \left[x ED^{b,hot}_{num,down}(M) + (1-x) ED^{b,cold}_{num,down}(M) \right] \end{aligned} \tag{F.4}$$

The first term is the transit provider's backbone cost for localized video traffic, which the transit provider delivers using cold potato routing. The second term is the transit provider's backbone cost for non-localized video traffic, which the transit provider delivers using hot potato routing.

Using the definition of the two traffic ratios r^{nv} and r^v, and the fact that $ED^{b,cold}_{num,down}(M) = 0$, equations (F.1)-(F.4) can be simplified. The traffic-sensitive backbone cost of the transit provider when peering with the ISP is:

$$\begin{aligned} C^{TP}_{(ISP-TP,M,x)} &= c^b (V_{up} + V^{v}_{down} x) ED^{b,hot}_{num,down}(M) \\ &= c^b V_{up} (1 + r^v x) ED^{b,hot}_{num,down}(M) \end{aligned} \tag{F.5}$$

Appendix G

Proof of Theorem 5.3

The peering fee that equalizes net costs is given by:

$$P^{TP,ISP} = \frac{1}{2}(C^{ISP}_{(ISP-TP,M,x)} - C^{TP}_{(ISP-TP,M,x)}) \tag{G.1}$$

If the ISP's traffic-sensitive backbone costs exceed those of the transit provider, then the fair peering fee is positive. If the transit provider's traffic-sensitive backbone costs exceed those of the ISP, then the fair peering fee is negative. By using Theorems 5.1 and 5.2, the fair peering fee can be expressed as:

$$P^{TP,ISP} = \frac{1}{2}c^b V_{up}\Big[\Big(r^{nv} - 1\Big) + \Big(r^v(1-x) - r^v x\Big)\Big] ED^{b,hot}_{num,down}(M) \tag{G.2}$$

The term $\frac{1}{2}c^b V_{up}(r^{nv}-1)ED^{b,hot}_{num,down}(M)$ is the fair peering fee resulting from any imbalance in the non-video traffic between the ISP and transit provider, similar to the case in which two ISPs peer. The term $\frac{1}{2}c^b V_{up} r^v (1-x) ED^{b,hot}_{num,down}(M)$ is the ISP's traffic-sensitive backbone cost incurred by non-localized video traffic. The term $-\frac{1}{2}c^b V_{up} r^v x ED^{b,hot}_{num,down}(M)$ is the transit provider's traffic-sensitive backbone cost incurred by localized video traffic. The terms can be combined. The fair peering fee between the transit provider and the ISP is:

$$P^{TP,ISP} = c^b V_{up}\Big[\frac{1}{2}(r^{nv}-1) + r^v(0.5-x)\Big] ED^{b,hot}_{num,down}(M) \tag{G.3}$$

Appendix H

Proof of Theorem 5.4

Using Theorems 5.1 and 5.2, the percentage of video traffic localization that equalizes the transit provider's and ISP's backbone costs is given by:

$$c^b V_{up}\Big[r^{nv} + r^v(1-x)\Big] ED^{b,hot}_{num,down}(M) = c^b V_{up}\Big[1 + r^v x\Big] ED^{b,hot}_{num,down}(M) \tag{H.1}$$

Solving for x gives:

$$x = \frac{r^{nv} + r^v - 1}{2r'} \tag{H.2}$$

Appendix I

Proof of Theorem 6.1

We determine the cost in the numerical model. The ISP's cost in this ISP-CP case is:

$$\begin{aligned} C^{ISP}_{num,(ISP-CP,N,x^d)} &= x^d C^{ISP}_{num,(ISP-CP,N,x^d=1)} + (1-x^d) C^{ISP}_{num,(ISP-CP,N,x^d=0)} \\ &= c^b V_{down} \left(x^d ED^{b,cold}_{2,down} + (1-x^d) ED^{b,hot}_{num,down} \right) \end{aligned} \tag{I.1}$$

where $ED^{b,hot}_{num,down}$ and $ED^{b,cold}_{2,down}$ are given in (3.18) and (3.21).

Appendix J

Proof of Theorem 6.2

Denote the cost-based peering fee between the transit provider and the ISP that is related solely to video traffic (not related to upstream or non-video downstream traffic) by $P_v^{TP,ISP}$. Using Theorem 5.3, we can determine $P_v^{TP,ISP}$ by considering only the video traffic component of the cost-based peering fee between the transit provider and the ISP ($P^{TP,ISP}$). It can be expressed as:

$$P_v^{TP,ISP} = c^b V_v (0.5 - x^d) ED_{num,down}^{b,hot}(M) \tag{J.1}$$

Denote the cost-based peering fee for direct interconnection between a content provider and an ISP by $P^{CP,ISP}$. It is given by:

$$P^{CP,ISP} = P_v^{TP,ISP} + (C_{num,(ISP-CP,N,x^d)}^{ISP} - C_{S,U,video}^{ISP}) \tag{J.2}$$

where $C_{num,(ISP-CP,N,x^d)}^{ISP}$ is the traffic-sensitive backbone cost of the ISP when peering with the content provider (given in Theorem **??**), and $C_{S,U,video}^{ISP}$ is the traffic-sensitive backbone cost of the ISP for delivering video traffic when peering with a transit provider (given in

(E.3)).

The cost difference $(C^{ISP}_{num,(ISP-CP,N,x^d)} - C^{ISP}_{S,U,video})$ accounts for any changes to the ISP's cost resulting from any differences in traffic flows and localization when it peers with a content provider rather than with a transit provider.

Using (E.3), (J.1) and Theorem **??**, we can express the cost-based peering fee in (J.2) as:

$$\begin{aligned} P^{CP,ISP} &= c^b V_v \Big[x^d ED^{b,cold}_{num,down}(N) \\ &+ (1 - x^d) ED^{b,hot}_{num,down}(N) - 0.5 ED^{b,hot}_{num,down}(M) \Big] \end{aligned} \tag{J.3}$$

Finally, we can rearrange the terms to separate the effects of the number of IXPs at which the content provider and the ISP peer from the effects of localization. The cost-based peering fee between the content provider and the ISP is:

$$\begin{aligned} P^{CP,ISP} &= c^b V_v \Big[\Big(0.5 - x^d\Big) ED^{b,hot}_{num,down}(M) \\ &+ \Big(1 - x^d\Big)\Big(ED^{b,hot}_{num,down}(N) - ED^{b,hot}_{num,down}(M)\Big) \\ &+ x^d \Big(ED^{b,cold}_{num,down}(N) - ED^{b,cold}_{num,down}(M)\Big)\Big] \end{aligned} \tag{J.4}$$

Appendix K

Proof of Theorem 7.1

The profit-maximizing prices (P^b, P^p, P^d) in (7.15) satisfy these first order conditions:

$$\frac{\partial \pi^{ISP}}{\partial P^b} = (P^b - C^b)\frac{\partial N^b}{\partial P^b} + (P^b + P^p - C^b - C^p)\frac{\partial N^p}{\partial P^b} + (P^b + P^p + P^d - C^b - C^p - C^d)\frac{\partial N^v}{\partial P^b} + N^b + N^p + N^v = 0. \tag{K.1}$$

$$\frac{\partial \pi^{ISP}}{\partial P^p} = (P^b - C^b)\frac{\partial N^b}{\partial P^p} + (P^b + P^p - C^b - C^p)\frac{\partial N^p}{\partial P^p} + (P^b + P^p + P^d - C^b - C^p - C^d)\frac{\partial N^v}{\partial P^p} + N^p + N^v = 0. \tag{K.2}$$

$$\frac{\partial \pi^{ISP}}{\partial P^d} = (P^b - C^b)\frac{\partial N^b}{\partial P^d} + (P^b + P^p - C^b - C^p)\frac{\partial N^p}{\partial P^d} + (P^b + P^p + P^d - C^b - C^p - C^d)\frac{\partial N^v}{\partial P^d} + N^v = 0. \tag{K.3}$$

We can rearrange these three equations in order to isolate the dependence on N^b, N^p, and

N^v:

$$(P^b - C^b)(\frac{\partial N^b}{\partial P^b} + \frac{\partial N^p}{\partial P^b} + \frac{\partial N^v}{\partial P^b} - \frac{\partial N^b}{\partial P^p} - \frac{\partial N^p}{\partial P^p} - \frac{\partial N^v}{\partial P^p}) + (P^p - C^p)(\frac{\partial N^p}{\partial P^b} + \frac{\partial N^v}{\partial P^b} - \frac{\partial N^p}{\partial P^p} - \frac{\partial N^v}{\partial P^p}) + (P^d - C^d)(\frac{\partial N^v}{\partial P^b} - \frac{\partial N^v}{\partial P^p}) + N^b = 0 \tag{K.4}$$

$$(P^b - C^b)(\frac{\partial N^b}{\partial P^p} + \frac{\partial N^p}{\partial P^p} + \frac{\partial N^v}{\partial P^p} - \frac{\partial N^b}{\partial P^d} - \frac{\partial N^p}{\partial P^d} - \frac{\partial N^v}{\partial P^d}) + (P^p - C^p)(\frac{\partial N^p}{\partial P^p} + \frac{\partial N^v}{\partial P^p} - \frac{\partial N^p}{\partial P^d} - \frac{\partial N^v}{\partial P^d}) + (P^d - C^d)(\frac{\partial N^v}{\partial P^p} - \frac{\partial N^v}{\partial P^d}) + N^p = 0 \tag{K.5}$$

$$(P^b - C^b)(\frac{\partial N^b}{\partial P^d} + \frac{\partial N^p}{\partial P^d} + \frac{\partial N^v}{\partial P^d}) + (P^p - C^p)(\frac{\partial N^p}{\partial P^d} + \frac{\partial N^v}{\partial P^d}) + (P^d - C^d)(\frac{\partial N^v}{\partial P^d}) + N^v = 0 \tag{K.6}$$

Applying the Leibniz Integral Rule to (7.4-7.6), we can show that the partial derivatives of demands with respect to prices are:

$$\begin{aligned} &\frac{\partial N^b}{\partial P^b} = -I4, \frac{\partial N^p}{\partial P^b} = -I6, \frac{\partial N^v}{\partial P^b} = -I1 \\ &\frac{\partial N^b}{\partial P^p} = I2 + I5, \frac{\partial N^p}{\partial P^p} = -I5 - I6, \frac{\partial N^v}{\partial P^p} = -I1 - I2 \\ &\frac{\partial N^b}{\partial P^d} = I2, \frac{\partial N^p}{\partial P^d} = I3, \frac{\partial N^v}{\partial P^d} = -I1 - I2 - I3 \end{aligned} \tag{K.7}$$

where

$$
\begin{aligned}
I1 &= N \int_{P^v}^{\infty} \int_{P^p+P^v-v}^{\infty} f_{B,P,V}(P^b + P^p + P^v - p - v, p, v)\ dp\ dv \\
I2 &= N \int_{P^v}^{\infty} \int_{P^b}^{\infty} f_{B,P,V}(b, P^p + P^v - v, v)\ db\ dv \\
I3 &= N \int_{P^p}^{\infty} \int_{P^b+P^p-p}^{\infty} f_{B,P,V}(b, p, P^v)\ db\ dp \\
I4 &= N \int_{-\infty}^{P^p} \int_{-\infty}^{P^p+P^v-p} f_{B,P,V}(P^b, p, v)\ dv\ dp \\
I5 &= N \int_{-\infty}^{P^v} \int_{P^b}^{\infty} f_{B,P,V}(b, P^p, v)\ db\ dv \\
I6 &= N \int_{-\infty}^{P^v} \int_{P^p}^{\infty} f_{B,P,V}(P^b + P^p - p, p, v)\ dp\ dv.
\end{aligned}
\tag{K.8}
$$

In (K.4-K.6), particular combinations of partial derivatives of demand with respect to price occur. It can be shown using (K.7) that:

$$
\frac{\partial N^p}{\partial P^d} + \frac{\partial N^v}{\partial P^d} = \frac{\partial N^v}{\partial P^p} \tag{K.9}
$$

$$
\frac{\partial N^b}{\partial P^d} + \frac{\partial N^p}{\partial P^d} + \frac{\partial N^v}{\partial P^d} = \frac{\partial N^v}{\partial P^b} \tag{K.10}
$$

$$
\frac{\partial N^b}{\partial P^p} - \frac{\partial N^b}{\partial P^d} + \frac{\partial N^p}{\partial P^p} - \frac{\partial N^p}{\partial P^d} + \frac{\partial N^v}{\partial P^p} - \frac{\partial N^v}{\partial P^d} = \frac{\partial N^p}{\partial P^b} \tag{K.11}
$$

$$
\frac{\partial N^v}{\partial P^b} - \frac{\partial N^v}{\partial P^p} = \frac{\partial N^b}{\partial P^d} \tag{K.12}
$$

$$\frac{\partial N^p}{\partial P^b} + \frac{\partial N^v}{\partial P^b} - \frac{\partial N^p}{\partial P^p} - \frac{\partial N^v}{\partial P^p} = \frac{\partial N^b}{\partial P^p} \tag{K.13}$$

We now substitute K.12 and K.13 into K.4, K.9 and K.11 into K.5, and K.9 and K.10 into K.6, to obtain:

$$\begin{aligned}
(P^b - C^b)\frac{\partial N^b}{\partial P^b} + (P^p - C^p)\frac{\partial N^b}{\partial P^p} + (P^d - C^d)\frac{\partial N^b}{\partial P^d} + N^b = 0 \\
(P^b - C^b)\frac{\partial N^p}{\partial P^b} + (P^p - C^p)\frac{\partial N^p}{\partial P^p} + (P^d - C^d)\frac{\partial N^p}{\partial P^d} + N^p = 0 \\
(P^b - C^b)\frac{\partial N^v}{\partial P^b} + (P^p - C^p)\frac{\partial N^v}{\partial P^p} + (P^d - C^d)\frac{\partial N^v}{\partial P^d} + N^v = 0
\end{aligned} \tag{K.14}$$

By rearranging (K.14), we can show that:

$$\begin{aligned}
\frac{P^b - C^b}{P^b}\frac{\partial N^b}{\partial P^b}\frac{P^b}{N^b} + \frac{P^p - C^p}{P^p}\frac{\partial N^b}{\partial P^p}\frac{P^p}{N^b} + \frac{P^d - C^d}{P^d}\frac{\partial N^b}{\partial P^d}\frac{P^d}{N^b} = -1 \\
\frac{P^b - C^b}{P^b}\frac{\partial N^p}{\partial P^b}\frac{P^b}{N^p} + \frac{P^p - C^p}{P^p}\frac{\partial N^p}{\partial P^p}\frac{P^p}{N^p} + \frac{P^d - C^d}{P^d}\frac{\partial N^p}{\partial P^d}\frac{P^d}{N^p} = -1 \\
\frac{P^b - C^b}{P^b}\frac{\partial N^v}{\partial P^b}\frac{P^b}{N^v} + \frac{P^p - C^p}{P^p}\frac{\partial N^v}{\partial P^p}\frac{P^p}{N^v} + \frac{P^d - C^d}{P^d}\frac{\partial N^v}{\partial P^d}\frac{P^d}{N^v} = -1
\end{aligned} \tag{K.15}$$

By using the definitions of the price elasticity of demand and the Lerner indices, it follows that the profit-maximizing prices (P^b, P^p, P^d) in (7.15) satisfy:

$$-\begin{bmatrix} \varepsilon_{N^b,P^b} & \varepsilon_{N^b,P^p} & \varepsilon_{N^b,P^d} \\ \varepsilon_{N^p,P^b} & \varepsilon_{N^p,P^p} & \varepsilon_{N^p,P^d} \\ \varepsilon_{N^v,P^b} & \varepsilon_{N^v,P^p} & \varepsilon_{N^v,P^d} \end{bmatrix} \begin{bmatrix} L^b \\ L^p \\ L^d \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \tag{K.16}$$

Appendix L

Proof of Theorem 7.2

Each elasticity in Theorem 7.2 is, by definition, the same sign as the related partial derivative. All integrals in K.8 are positive, since the joint density function $f_{B,P,V}$ is positive. By using K.7, it follows that:

$$\begin{aligned}
\varepsilon_{N^b,P^b} &\triangleq \frac{\partial N^b}{\partial P^b}\frac{P^b}{N^b} = -(I4)\frac{P^b}{N^b} < 0 \\
\varepsilon_{N^b,P^p} &\triangleq \frac{\partial N^b}{\partial P^p}\frac{P^p}{N^b} = (I2+I5)\frac{P^p}{N^b} > 0 \\
\varepsilon_{N^b,P^d} &\triangleq \frac{\partial N^b}{\partial P^d}\frac{P^d}{N^b} = (I2)\frac{P^d}{N^b} > 0 \\
\varepsilon_{N^p,P^b} &\triangleq \frac{\partial N^p}{\partial P^b}\frac{P^b}{N^p} = -(I6)\frac{P^b}{N^p} < 0 \\
\varepsilon_{N^p,P^p} &\triangleq \frac{\partial N^p}{\partial P^p}\frac{P^p}{N^p} = -(I5+I6)\frac{P^p}{N^p} < 0 \\
\varepsilon_{N^p,P^d} &\triangleq \frac{\partial N^p}{\partial P^d}\frac{P^d}{N^p} = (I3)\frac{P^d}{N^p} > 0 \\
\varepsilon_{N^v,P^b} &\triangleq \frac{\partial N^v}{\partial P^b}\frac{P^b}{N^v} = -(I1)\frac{P^b}{N^v} < 0 \\
\varepsilon_{N^v,P^p} &\triangleq \frac{\partial N^v}{\partial P^p}\frac{P^p}{N^v} = -(I1+I2)\frac{P^p}{N^v} < 0 \\
\varepsilon_{N^v,P^d} &\triangleq \frac{\partial N^v}{\partial P^d}\frac{P^d}{N^v} = -(I1+I2+I3)\frac{P^d}{N^v} < 0.
\end{aligned} \tag{L.1}$$

Appendix M

Proof of Theorem 7.3

Applying the Leibniz Integral Rule to (7.7-7.9), we can show that the partial derivatives of each consumer surplus with respect to prices are:

$$\begin{aligned}
&\frac{\partial CS^b}{\partial P^b} = -N^b, \frac{\partial CS^p}{\partial P^b} = -N^p, \frac{\partial CS^v}{\partial P^b} = -N^v \\
&\frac{\partial CS^b}{\partial P^p} = I9 + I7, \frac{\partial CS^p}{\partial P^p} = -I9 - N^p, \frac{\partial CS^v}{\partial P^p} = -I7 - N^v \\
&\frac{\partial CS^b}{\partial P^v} = I7, \frac{\partial CS^p}{\partial P^v} = I8, \frac{\partial CS^v}{\partial P^v} = -I7 - I8 - N^v
\end{aligned} \tag{M.1}$$

where

$$\begin{aligned}
I7 &= N \int_{-\infty}^{P^p} \int_{P^b}^{\infty} (b - P^b) f_{B,P,V}(b, p, P^p + P^v - p)\, db\, dp \\
I8 &= N \int_{P^p}^{\infty} \int_{P^b + P^p - p}^{\infty} (b + p - P^b - P^p) f_{B,P,V}(b, p, P^v)\, db\, dp \\
I9 &= N \int_{-\infty}^{P^v} \int_{P^b}^{\infty} (b - P^b) f_{B,P,V}(b, P^p, v)\, db\, dv
\end{aligned} \tag{M.2}$$

Using (7.10) and (M.1), we can calculate the partial derivative of total consumer surplus respect to each price:

$$\begin{aligned}
\frac{\partial CS}{\partial P^b} &= \frac{\partial CS^b}{\partial P^b} + \frac{\partial CS^p}{\partial P^b} + \frac{\partial CS^v}{\partial P^b} = -N^b - N^p - N^v \\
\frac{\partial CS}{\partial P^p} &= \frac{\partial CS^b}{\partial P^p} + \frac{\partial CS^p}{\partial P^p} + \frac{\partial CS^v}{\partial P^p} = -N^p - N^v \\
\frac{\partial CS}{\partial P^v} &= \frac{\partial CS^b}{\partial P^v} + \frac{\partial CS^p}{\partial P^v} + \frac{\partial CS^v}{\partial P^v} = -N^v
\end{aligned} \tag{M.3}$$

Equation (7.27) follows.

Appendix N

Proof of Theorem 7.4

To solve the nonlinear optimization problem with constraints, we use the Karush–Kuhn–Tucker (KKT) theorem. The Lagrangian function of (7.30) is:

$$\begin{aligned}
\mathcal{L} &= CS^b + CS^p + CS^v + \lambda_1[P^v - P^d - (r_{\min}^{VSP} + 1)C^v] \\
&+ \lambda_2[(P^b - (r_{\min}^{ISP} + 1)C^b)N^b + (P^b + P^p - (r_{\min}^{ISP} + 1)(C^b + C^p))N^p \\
&+ (P^b + P^p + P^d - (r_{\min}^{ISP} + 1)(C^b + C^p + C^d))N^v]
\end{aligned} \tag{N.1}$$

There exist KKT multipliers (λ_1 and λ_2), such that the following conditions hold.

Stationarity:

$$\begin{aligned}
\frac{\partial \mathcal{L}}{\partial P^b} &= 0 \\
\frac{\partial \mathcal{L}}{\partial P^p} &= 0 \\
\frac{\partial \mathcal{L}}{\partial P^d} &= 0 \\
\frac{\partial \mathcal{L}}{\partial P^v} &= 0
\end{aligned} \tag{N.2}$$

Complementary slackness:

$$\begin{aligned}
&\lambda_1[P^v - P^d - (r_{\min}^{VSP} + 1)C^v] = 0 \\
&\lambda_2[(P^b - (r_{\min}^{ISP} + 1)C^b)N^b + (P^b + P^p - (r_{\min}^{ISP} + 1)(C^b + C^p))N^p \\
&+ (P^b + P^p + P^d - (r_{\min}^{ISP} + 1)(C^b + C^p + C^d))N^v] = 0
\end{aligned} \tag{N.3}$$

Feasibility:

$$\begin{aligned}
&\lambda_1 \geq 0 \\
&\lambda_2 \geq 0
\end{aligned} \tag{N.4}$$

Since there are 2 constraints in (N.3), there are 4 different cases depending on which of the constraints are binding. After investigation, we concluded that both constraints are binding. It follows that:

$$\begin{aligned}
&P^v = (r_{\min}^{VSP} + 1)C^v + P^d \\
&(P^b - (r_{\min}^{ISP} + 1)C^b)N^b + (P^b + P^p - (r_{\min}^{ISP} + 1)(C^b + C^p))N^p \\
&+ (P^b + P^p + P^d - (r_{\min}^{ISP} + 1)(C^b + C^p + C^d))N^v = 0
\end{aligned} \tag{N.5}$$

Using (N.5) and (7.27), we can calculate the partial derivative of the Lagrangian with respect to each price:

$$
\begin{aligned}
&\frac{\partial \mathcal{L}}{\partial P^b} = \lambda_2[(P^b - (r_{\min}^{ISP} + 1)C^b)\frac{\partial N^b}{\partial P^b} + (P^b + P^p - (r_{\min}^{ISP} + 1)(C^b + C^p))\frac{\partial N^p}{\partial P^b} \\
&+ (P^b + P^p + P^d - (r_{\min}^{ISP} + 1)(C^b + C^p + C^d))\frac{\partial N^v}{\partial P^b} + N^b + N^P + N^v] - N^b - N^P - N^v = 0 \\
&\frac{\partial \mathcal{L}}{\partial P^p} = \lambda_2[(P^b - (r_{\min}^{ISP} + 1)C^b)\frac{\partial N^b}{\partial P^p} + (P^b + P^p - (r_{\min}^{ISP} + 1)(C^b + C^p))\frac{\partial N^p}{\partial P^p} \\
&+ (P^b + P^p + P^d - (r_{\min}^{ISP} + 1)(C^b + C^p + C^d))\frac{\partial N^v}{\partial P^p} + N^P + N^v] - N^P - N^v = 0 \\
&\frac{\partial \mathcal{L}}{\partial P^d} = \lambda_2[(P^b - (r_{\min}^{ISP} + 1)C^b)\frac{\partial N^b}{\partial P^d} + (P^b + P^p - (r_{\min}^{ISP} + 1)(C^b + C^p))\frac{\partial N^p}{\partial P^d} \\
&+ (P^b + P^p + P^d - (r_{\min}^{ISP} + 1)(C^b + C^p + C^d))\frac{\partial N^v}{\partial P^d} + N^v] - N^v = 0
\end{aligned}
\tag{N.6}
$$

The prices in (7.31) satisfy both (N.5) and (N.6). The theorem follows.

Appendix O

Derivation of Lerner Rule for the New Basis

By using the definitions of the Lerner indices in (7.16), we have:

$$-\begin{bmatrix} \varepsilon_{N^x,P^x} & \varepsilon_{N^x,P^y} \\ \varepsilon_{N^y,P^x} & \varepsilon_{N^y,P^y} \end{bmatrix} \begin{bmatrix} \frac{P^x-C^x}{P^x} \\ \frac{P^y-C^y}{P^y} \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix} \tag{O.1}$$

By using the definition of the price elasticity of demand, we have:

$$-\begin{bmatrix} \frac{\partial N^x}{\partial P^x} & \frac{\partial N^x}{\partial P^y} \\ \frac{\partial N^y}{\partial P^x} & \frac{\partial N^y}{\partial P^y} \end{bmatrix} \begin{bmatrix} P^x - C^x \\ P^y - C^y \end{bmatrix} = \begin{bmatrix} N^x \\ N^y \end{bmatrix} \tag{O.2}$$

By rearranging (O.2), we can show that:

$$-\begin{bmatrix} \frac{\partial N^x}{\partial P^x} + \frac{\partial N^x}{\partial P^y} & \frac{\partial N^x}{\partial P^y} \\ \frac{\partial N^y}{\partial P^x} + \frac{\partial N^y}{\partial P^y} & \frac{\partial N^y}{\partial P^y} \end{bmatrix} \begin{bmatrix} P^x - C^x \\ (P^y - C^y) - (P^x - C^x) \end{bmatrix} = \begin{bmatrix} N^x \\ N^y \end{bmatrix} \tag{O.3}$$

By using the fact that $N^b = N^x$, $N^p = N^y$, $C^x = C^b$, and $C^y = C^b + C^p$, we can rewrite (O.3) as:

$$-\begin{bmatrix} \frac{\partial N^b}{\partial P^x} + \frac{\partial N^b}{\partial P^y} & \frac{\partial N^b}{\partial P^y} \\ \frac{\partial N^p}{\partial P^x} + \frac{\partial N^p}{\partial P^y} & \frac{\partial N^p}{\partial P^y} \end{bmatrix} \begin{bmatrix} P^b - C^b \\ P^p - C^p \end{bmatrix} = \begin{bmatrix} N^b \\ N^p \end{bmatrix} \tag{O.4}$$

By using (7.17), we can define demand as a function of P^x and P^y:

$$N^b(P^x, P^y) = N \int_{-\infty}^{P^y - P^x} \int_{P^x}^{\infty} f_{B,P}(b,p)\, db\, dp. \tag{O.5}$$

$$N^p(P^x, P^y) = N \int_{P^y - P^x}^{\infty} \int_{P^y - p}^{\infty} f_{B,P}(b,p)\, db\, dp. \tag{O.6}$$

Applying the Leibniz Integral Rule to (O.5) and (O.6), we can show that the partial derivatives of demands with respect to prices are:

$$\begin{aligned} \frac{\partial N^b}{\partial P^x} &= \frac{\partial N^b}{\partial P^b} - \frac{\partial N^b}{\partial P^p} \\ \frac{\partial N^b}{\partial P^y} &= \frac{\partial N^b}{\partial P^p} \\ \frac{\partial N^p}{\partial P^x} &= \frac{\partial N^b}{\partial P^p} \\ \frac{\partial N^p}{\partial P^y} &= \frac{\partial N^p}{\partial P^p} \\ \frac{\partial N^p}{\partial P^b} &= \frac{\partial N^p}{\partial P^p} + \frac{\partial N^b}{\partial P^p} \end{aligned} \tag{O.7}$$

We now substitute (O.7) into (O.4) to obtain:

$$-\begin{bmatrix} \frac{\partial N^b}{\partial P^b} & \frac{\partial N^b}{\partial P^p} \\ \frac{\partial N^p}{\partial P^b} & \frac{\partial N^p}{\partial P^p} \end{bmatrix} \begin{bmatrix} P^b - C^b \\ P^p - C^p \end{bmatrix} = \begin{bmatrix} N^b \\ N^p \end{bmatrix} \tag{O.8}$$

By rearranging (O.8):

$$-\begin{bmatrix} \frac{\partial N^b}{\partial P^b}\frac{P^b}{N^b} & \frac{\partial N^b}{\partial P^p}\frac{P^p}{N^b} \\ \frac{\partial N^p}{\partial P^b}\frac{P^b}{N^p} & \frac{\partial N^p}{\partial P^p}\frac{P^p}{N^p} \end{bmatrix} \begin{bmatrix} \frac{P^b-C^b}{P^b} \\ \frac{P^p-C^p}{P^p} \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix} \tag{O.9}$$

By using the definitions of the price elasticity of demand and the Lerner indices, equation (7.18) follows.