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Localizing Internet infrastructure: Cooperative peering in Latin America

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ABSTRACT

This paper offers an overview of the changes in the Internet interconnection regime in the past decade and their key implications for the development of Internet infrastructure in developing regions based on the Latin American experience. The main argument presented is that changes in market conditions and Internet traffic patterns over the past decade have favored the search for new interconnection arrangements between actors located at the outer edges of the traditional Internet topology. Driven by the need to control operating costs and optimize content delivery to end-users, network operators in Latin America (and elsewhere in developing regions) are increasingly experimenting with cooperative peering arrangements to meet interconnection needs. The evidence suggests that these new arrangements are resulting in multiple benefits to local Internet ecosystems, among them reduced transit costs, greater network redundancy, improved service quality, new infrastructure investments and better technical coordination among operators.

1. Introduction

As a network of networks, the Internet critically depends on adequate arrangements for traffic exchange between the different participants in the Internet ecosystem. These interconnection contracts have changed significantly over the past decades, driven by changes in policy frameworks, in the scale of Internet traffic and its patterns, and in the goals and incentives of participating actors. The hierarchical, U.S.-centric Internet architecture that characterized the 1990s has given way to a flatter and more globally dispersed network populated by a less homogeneous set of market actors. While these changes have disrupted the existing interconnection regime, at the same time they have allowed the emergence of new cooperative arrangements by actors located at the outer edges of the Internet topology.

This paper offers an overview of these changes and their key implications for the development of Internet infrastructure in emerging countries based on the recent Latin American experience. To a large extent, this analysis can be extended to other developing regions, though variations in infrastructure deployment, policy frameworks, geographical location and other factors must be considered in each particular case. The main argument presented is that changes in market conditions and Internet traffic patterns over the past decade have favored the search for new interconnection arrangements between network operators in emerging countries. Driven by the need to control costs and optimize content delivery to end-users, network operators in Latin America (and elsewhere in developing regions) are increasingly experimenting with cooperative peering arrangements to meet interconnection needs. The evidence suggests that these new arrangements are resulting in

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multiple benefits to local Internet ecosystems, among them reduced transit costs, greater network redundancy, improved service quality, new infrastructure investments and better technical coordination among operators.

This paper draws from two types of primary data. First, personal interviews were conducted with representatives of key stakeholders, including Internet Service Providers (henceforth ISPs), content providers, Internet Exchange Point (henceforth IXP) operators, and relevant regional organizations such as LACNIC and LAC-IX.[1] Second, active network probes were deployed in Bolivia in order to obtain end-user measurements for different QoS parameters following the implementation of a new interconnection regime in November 2013. In addition, secondary data about interconnections arrangements in Latin America was obtained from various sources, including the Packet Clearing House (PCH)'s peering database and LAC-IX.

The paper is organized as follows: Section 2 provides a brief overview of the changes in the Internet interconnection regime over the past decade, with emphasis on the emergence of cooperative peering arrangements among ISPs in developing regions. This is followed in Section 3 by a more detailed discussion of the evolution of such arrangements in Latin America. Section 4 documents the impact of IXPs in Latin America, drawing evidence from case studies in Argentina, Brazil, Bolivia, Colombia and Ecuador. Section 5 offers policy recommendations for stimulating cooperative arrangements for local traffic exchange while preserving the light-touch regulatory approach that has allowed the Internet to flourish.

2. The evolution of Internet interconnection

At its core, the Internet is a sparse mesh of independent networks that exchange data packets using a common set of communication protocols. These independent networks are administered autonomously, serving different goals and occupying different spaces in the Internet architecture. In the early days (until the mid-1990s) the Internet presented a clear hierarchy between a few large networks interconnected at the core (the so-called Tier-1 operators, by and large located in the U.S. and Europe), and a vast number of national/regional (so-called Tier-2) and local (Tier-3) networks. As Faratin et al. (2007) argue, the key distinction between these networks was their size, measured by geographical reach, traffic volume and number of customers. Yet they were remarkably similar with respect to the services offered and their traffic patterns.

The result was an interconnection regime characterized by two basic types of contracts:

1. *Peering.* In a peering agreement two or more network operators (e.g., two Tier-1 operators) agree to exchange IP traffic at no cost by providing each other access to their customer base. The decision to peer is a matter of negotiation between the parties, and generally requires that networks share similar characteristics in terms of network capacity, geographical coverage and QoS. Since peering is settlement-free, these requirements seek to ensure that costs are approximately symmetrical between peering parties. Peering can be further divided into *private peering*, in which two parties establish point-to-point transport between them over a dedicated link, and *public peering*, which refers to the exchange of traffic at third-party locations to which other operators are also connected.
2. *Transit.* In a transit arrangement, a network operator (e.g., a local ISP) pays another operator (e.g., a backbone provider) to deliver packets to any Internet destination, and to receive packets from any destination. Typically, transit is sold at a single rate (expressed in price per Mbps per month) regardless of the origin/destination of the packets. While volume discounts are typical, the key fact is that rates do not vary according to actual delivery costs (e.g., whether traffic is offloaded on-net or off-net, whether it is delivered to a neighboring network or to a network in a different continent, and so forth). As Valancius et al. (2011) show, this crude form of pricing is one of the factors that has led ISPs in developing countries to search for alternatives to transit.[2]

It is important to note that, while in a peering arrangement the parties will only have access to each other's downstream customers (in other words it is not transitive to other agreements the parties may have), in a transit agreement the paying party buys access to all Internet destinations from the selling party. Peering therefore requires agreements with multiple other parties in order to reach all possible Internet destinations, while a single transit connection allows a network operator to access the entire Internet.

Until the early 2000s, peering arrangements were by and large limited to the large backbone operators located in developed countries, while in the outer edges operators typically bought transit in order to reach these core networks (where much of the content was hosted) as well as to exchange traffic with other network operators, even geographically adjacent ones. This often resulted in international tromboning, a practice whereby adjacent ISPs in emerging countries exchanged traffic not bilaterally but rather over international transit routes provisioned by backbone operators. This practice increased costs and decreased service quality for customers of networks at the bottom of the Internet hierarchy (Lie, 2007).

[1] LACNIC is the Latin American and Caribbean Internet Addresses Registry, responsible for assigning and administrating Internet numbering resources, Autonomous System Numbers (ASNs), and other resources for the region of Latin America and the Caribbean. LAC-IX is an association of IXP operators in Latin America and the Caribbean.

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Today's Internet architecture is less of a hierarchy than a complex mesh of peering and transit agreements between a more heterogeneous set of network operators (Yoo, 2010; Clark et al., 2011). The new topology is being shaped by several trends, two of which are worth highlighting. The first is the fast growth in Internet access and use outside the developed world. As the ITU (2014) reports, the share of Internet users living in developed countries has dropped from 60% in 2005 to 34% in 2014, quickly approaching the actual world population distribution (about 20% of the world's population lives in developed countries). Capacity demand is therefore much more geographically distributed across regions, requiring new infrastructure investments outside the traditional Internet's core.

The second trend is the rapid growth of traffic volumes, much of which is explained by two applications: filesharing and video streaming. In particular, the exponential growth of videostreaming has resulted in the emergence of specialized networks dedicated to content delivery, whose traffic patterns are largely asymmetrical (i.e., small inbound/large outbound patterns) and whose revenues stem primarily from advertising. The emergence of these content distribution networks (CDNs) has unsettled the established interconnection regime, opening up opportunities for bypassing Tier-1 networks and creating new interconnection arrangements such as paid peering and partial transit (Faratin et al., 2007; Valancius et al., 2011).

Table 1 shows how traffic grew at an annual rate of between 48% (average) and 56% (peak) in Latin America between 2008 and 2012. This has strained capacity on access networks, particularly for small and medium-sized ISPs which are not vertically integrated into backbone provision and are thus are more dependent on transit arrangements. Table 2 shows how transit prices in key Latin American cities also dropped during this period, but at a much slower rate than the growth in traffic (with the exception of Mexico, which is a unique case due to its geographical proximity to the U.S.).

In response to these trends, ISPs in Latin America (and elsewhere in the developing world) have adopted several strategies aimed at balancing the need to meet growing traffic demands with the need to keep transit costs under control. One of these strategies has been to expand cooperative peering arrangements with neighboring network operators. Under this model, long used by network operators in Europe, ISPs agree to exchange traffic at a local exchange point, which is set up as a non-profit organization and managed cooperatively by its members.

The general benefits of public peering for network operators are well-documented in the literature (Chatzis et al., 2013; Kende and Hurpy, 2012; Sowell, 2013; Weller and Woodcock, 2013). They include:

(a) *Lower interconnection costs.* A single link to an IXP allows peering with multiple other operators. In turn, the more parties are connected to an IXP, the more valuable it becomes, in a classic case of direct network externalities. In contrast, as Sowell (2013) shows, private peering often entails a static investment decision with high sunk costs for contracting parties.
(b) *Enhanced quality of service.* IXPs reduce the number of hops for data packets traveling between peering parties, thereby reducing latency and jitter (Weller and Woodcock, 2013).[3] In particular, when content distribution networks (CDNs) peer directly at IXPs, the quality of access to popular content is dramatically increased.

For a number of reasons, the presence of a local IXP is particularly critical for the growth of the Internet ecosystem in emerging countries. First, local exchange points allow traffic generated by neighboring ISPs to remain local, thus reducing international transit needs and providing incentives for the growth of local hosting services (Kende and Rose, 2015). As shown below, international transit represents an important cost factor for ISPs in emerging countries, given that much of the content and many of the most popular cloud-based applications are hosted in foreign servers. These costs can be even higher for ISPs in countries where international bandwidth is under-provisioned due to poor access to submarine cable capacity (e.g., mediterranean countries such as Bolivia) and/or monopoly control of international gateways by incumbents (see Garcia-Zaballos et al., 2011).

Second, IXPs have a positive impact on QoS through several mechanisms. Keeping traffic local reduces latency and jitter due to shorter routing paths. As traffic at the IXP increases, this creates incentives for large content providers to place their content closer to end-users by installing caches at the IXP or creating more direct routes to server hosts. As discussed below, direct peering by large CDNs is a key success factor for IXPs in developing regions.

Finally, IXPs play an important role in promoting Internet development in areas serviced by small and medium-size ISPs, which tend to be poorer and more isolated than those serviced by larger ISPs.[4] By peering at an IXP, small-scale operators are able to reduce transit costs not only by exchanging traffic locally but also by collectively negotiating better transit prices, as well as attracting peering from content providers. Section 4 explores each of these mechanisms in more detail, drawing from examples across Latin America.

3. IXPs Latin America and the Caribbean: stylized facts

As of 2014 there were over 50 IXPs operating in Latin America and the Caribbean in 15 different countries.[5] This means that only about a third of the countries in the region (including dependent territories) have an operational IXP. For comparison,

[3] Latency is a measure of the amount of time (typically measured in milliseconds) that it takes for a data packet to be transmitted from its source to its destination. Jitter is the variation in latency.

[4] This is documented, among others, by Galperin and Bar (2007) and Aranha et al. (2011).

[5] Source: Packet Clearing House and author analysis. This excludes exchange points run by operators themselves such as in the case of Chile.

Table 1
International Internet Traffic in Latin America (in Gbps), 2008–2012.

	2008	2009	2010	2011	2012	CAGR (%)
Average	345	564	841	1242	1675	48
Peak	552	892	1359	2365	3303	56

Source: Telegeography.

Table 2
Median IP Transit Prices (in USD) per Mbps/month in Latin America, 2010–2012.

	2010	2011	2012	2013	CAGR (%)
Buenos Aires	42	39	27	25	−16
Lima	65	48	38	35	−19
Mexico City	40	28	8.5	6.3	−46
Rio de Janeiro	48	40	27	25	−20
Santiago de Chile	47	40	29	27	−17
São Paulo	50	39	27	25	−21

Source: Telegeography.

there are 25 IXPs in Africa located in 19 countries (also about a third of the countries in the continent), 88 in North America (U.S. and Canada) and over 130 in Europe. Yet the situation differs significantly across the region. While IXPs are present in most countries in South America (though with varying levels of development), Central America is home to only two IXPs (in Panama and Costa Rica).

The first IXPs in the region were established in the late 1990s. Until then, the lack of local peering points was largely a result of two factors. The first factor was the early development of the core Internet infrastructure in the Unites States, discussed in the previous section. As a result, local ISPs competed on the basis of price/quality of their routes to the United States. Since traffic within the countries or region was very limited, tromboning this traffic through international transit routes represented a cost-effective solution. The second factor was the relatively slow pace of the liberalization of telecommunications markets, which kept domestic transport prices high, thus discouraging local peering (Katz et al., 2013).

The ground became significantly more fertile for IXPs in Latin America in the late 90s. On the one hand, the benefits of market reforms in the telecommunications sector implemented during the early 1990s began to materialize, as competition from new entrants began to exert downward pressure on domestic transport prices (Gutierrez and Berg, 2000). Further, as the base of subscribers grew and infrastructure investment intensified, more content began to be hosted locally. Fig. 1 corroborates the steady growth of IXPs in the region since 1999.

By international standards IXPs in Latin America tend to be relatively small, peering on average 12 networks (slightly more in South America and less in the Caribbean). The exception is PTT Metro São Paulo, by far the largest in the region, where over 300 networks exchange traffic, making it the seventh-largest worldwide in terms of participants (for comparison, large IXPs in Europe are peering over 500 networks). Most IXPs in the region are operated as non-commercial organizations administered by its members or under the umbrella of trade associations. Under this model, operational costs are typically shared proportionally to the number of ports and capacity (such as rack space) utilized by each member. When additional services (such as transport and access to content caches) are offered, costs are allocated according to actual traffic generated by each participant.

Interestingly, many IXPs in the region enforce multilateral peering policies. In a multilateral peering agreement, all network operators are required to peer with each other at the IXP. This mandate creates negative incentives for large operators to participate, as it facilitates market entry and reduces transit costs for smaller competitors. Yet without the largest market actors, the viability of an IXP can be severely compromised. This was the case in Argentina, where NAP Buenos Aires, the first IXP in the region, saw its traffic drop dramatically after the four largest operators decided to de-peer from the exchange in 2004. As discussed in the next section, it took many years for NAP Buenos Aires to reinvent itself as a distributed IXP with national reach.

The volume of traffic exchanged at IXPs in the region varies widely. PTT Metro in São Paulo exchanged over 300 Gbps (daily average) in 2014. On the other hand, IXPs located in smaller countries or at the local (e.g., municipal) level exchanged 100 Mbps or less. For comparison, the largest European IXPs exchange over 2 Tbps during peak times. Whether the incumbent telecom operator in the country participates in the IXP is a key factor determining traffic volumes. Unlike other regions such as Europe and Asia, it is uncommon for network operators based in one country to establish a presence in an IXP located in another country.[6]

The regulatory framework for IXPs also varies across Latin America. Until recently few countries had legislation affecting IP interconnection. The key exception was Chile, where the regulator required that ISPs implement the means for the

[6] An exception is the presence of Uruguayan operator Antel as a member of NAP CASBASE in Buenos Aires, Argentina.

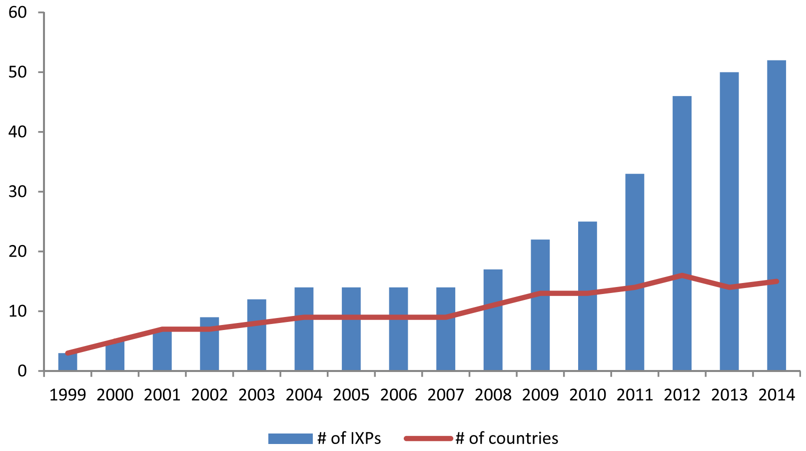

Fig. 1. IXPs in Latin America, 1999–2014. Source: author's own analysis based on data from Packet Clearing House (www.pch.net).

exchange of local traffic, though the mandate did not specifically favor public peering.[7] As a result most peering points are run by operators themselves. This has changed recently, with several countries passing new telecom interconnection regimes that explicitly address IP interconnection. In Bolivia, a new interconnection law passed in 2013 required the establishment of a neutral IXP for the exchange of traffic between local ISPs, specifying some its key operational characteristics.[8] In other cases, legislation aimed at promoting competition in the telecoms sector has favored the growth of IXPs. Such is the case of Brazil, where the regulator has required that network operators with significant market power connect to existing IXPs (or establish one themselves in areas where none exist).[9]

4. IXPs in action: evidence from case studies

As discussed in Section 2, previous studies suggests that IXPs positively affect Internet growth by reducing transit costs, increasing service quality, promoting local content hosting, and creating incentives for infrastructure investments in small and medium-size markets. This section elaborates on each of these mechanisms, drawing evidence from case studies of IXPs in several Latin American countries.

4.1. Impact on transit costs

The economics of the IP transit market are such that low contracted volumes are strongly associated with higher per unit costs. International transit is therefore a significant cost factor for small and medium-sized ISPs in Latin America. Take for example the case of AXS in Bolivia, a medium-sized operator with presence in Bolivia's three largest cities (La Paz, Cochabamba and Santa Cruz). From an analysis of its financial statements it results that international transit costs represented 38% of total operating costs for AXS in 2013. The figure is lower for other operators whose revenues depend more on traditional telephony services. Yet if calculated as a percentage of revenues from data services (including Internet access), international transit costs climb up to 24% for COTAS and 18% for ENTEL, the two largest operators. Not surprisingly, Internet access costs in Bolivia are among the highest in the region (Galperin, 2013).

Until recently, Ecuador faced a similar problem. While not a mediterranean country, the underprovisioning of international capacity severely restricted the development of Internet services in the country. In particular, Ecuador was bypassed by the main submarine cable on the western coast of the continent (the SAm-1 cable). Direct international connectivity was restricted to the older Pan-American cable, in which capacity was often saturated. Much international traffic was routed through Colombia, adding significant transport costs. Not surprisingly, Internet services in Ecuador were also among the most expensive in the region, as ISPs faced steep transit costs on their international routes (Albornoz and Agüero, 2011).

The establishment of NAP.EC, the first IXP in Ecuador, in 2001 was a direct response to this problem. NAP.EC was initially formed by six ISPs as a non-profit organization, with the primary goal of reducing transit costs. Two exchange points were established in the cities of Quito and Guayaquil, which were later interconnected in 2007. In 2010, a third exchange point was opened in the city of Cuenca. While the original members were small to medium-size ISPs, larger operators (such as the state-controlled incumbent CNT) and content providers were progressively interconnected. By mid-2013 over 20

7 SUBTEL Resolution 1483, October 1999.
8 ATT Resolution 0482/2013.
9 ANATEL Resolution 600, November 2012.

networks were exchanging traffic at NAP.EC, including international backbone operators such as Level 3, large content distributors such as Google and Akamai, and most local ISPs.

The costs savings made possible by NAP.EC can be estimated as follows: in mid-2013 NAP.EC exchanged about 6 Gbps during peak hours. International transit costs for the capital city of Quito hovered around USD $100 per Mbps per month.[10] By contrast, traffic was exchanged at NAP.EC for as little as USD $1 per Mbps per month. Assuming that in the absence of NAP.EC operators would need to exchange traffic through international transit routes (i.e., assuming no bilateral peering), the additional wholesale costs for local ISPs would amount to USD $7.2 million per year. Even discounting the costs associated with peering at the IXP (transport to the IXP facilities, membership fees and routing/switching equipment) and bilateral peering for part of this traffic, the annual cost savings associated with NAP.EC remain very significant.

The case of Argentina illustrates a related mechanism through which IXPs contribute to reduce transit costs, particularly in smaller markets. Argentina ranks high in Internet adoption in the region, and in contrast to Bolivia and Ecuador has abundant international bandwidth capacity, which has helped keep international transit prices relatively low in regional comparison (see Table 2). Yet due to high domestic transport prices, ISPs outside the primary fiber routes connecting Buenos Aires with other large cities face significant transit costs. Moreover, transit services are often available exclusively from the former telecommunications incumbent, which also competes with its own Internet retail services. As a result, access prices remained significantly higher in less populated cities, thus slowing market growth.[11]

Drawing on its experience operating NAP Buenos Aires, CABASE, a trade association of network operators, embarked on an initiative to establish IXPs in small and medium-sized markets across Argentina. The new IXPs, set up under cooperative arrangements, not only allowed local network operators to exchange traffic but also to interconnect through NAP Buenos Aires, thus forming a virtual IXP with national reach. The first regional IXP was established in the southern city of Neuquén in May 2011. By 2014 13 regional IXPs were in operation, connecting over 100 networks through a central routing hub in NAP Buenos Aires.

The cost benefits associated with this initiative can be divided into (a) savings resulting from lower transit prices and (b) savings from peering at the local traffic exchange. By aggregating traffic at the IXP, small network operators were able to negotiate better terms with upstream transit providers. For example, in the city of San Martin de los Andes (population 25,000), Internet transit costs were as high as USD $500 per Mbps per month for COTESMA, a local telecoms cooperative. Once the Neuquén IXP became operational, COTESMA was able to buy Internet transit at the IXP premises for USD $100 per Mbps per month. As more IXPs were established the national transit market was further disrupted, with prices across the country progressively converging to those of Buenos Aires (about USD $25 per Mbps per month).

The cost savings associated with the CABASE initiative can be estimated as follows. According to interviews with small network operators connected to different regional IXPs, about 60% of their traffic stays within the CABASE network (which includes caches from CDNs such as Google and Akamai), while the remaining 40% uses international transit links. Traffic within CABASE network can be further broken down into local traffic (25%) and CDN traffic (35%). Local traffic is subject to transport costs (to connect regional IXPs to the Buenos Aires hub) which amount to about USD $15 per Mbps, while CDN traffic is subject to caching costs that average USD $1 per Mbps. As Table 3 shows, for a small operator outside Buenos Aires contracting 200 Mbps of upstream capacity, the presence of a local IXP can reduce costs by as much as half (note that the baseline scenario uses a conservative estimate of USD $60 for transit costs).

4.2. Impact on service quality

Service[12] quality is an important driver for the development of local Internet ecosystems. Several studies reveal that high latency discourages adoption and reduces use (Kende and Rose, 2015). Poor quality also stymies the growth of over-the-top (OTT) players (particularly in VoIP, gaming and video streaming services), while it encourages content providers to host outside the country, limiting the scale of the local market and thus further aggravating quality. In the absence of higher-quality services, local Internet markets tend to be trapped in a low equilibrium of limited adoption, low traffic volumes, slow download speeds, little local content, expensive local hosting, and ultimately slow Internet growth.

As the Colombian case illustrates, the presence of a local IXP can help unlock growth by reducing latency, increasing route redundancy, and facilitating content location closer to end-users. The Colombian exchange point NAP Colombia was started in 2000 in response to the frequent disruptions in the domestic transport lines and international links of the incumbent telecommunications operator Colombia Telecom. By exchanging traffic at the IXP, and later by installing caches of large content providers, local ISPs were able to reduce their dependence on international routes, thus reducing costs but, most importantly, increasing reliability. Today, while the physical infrastructure is more robust and outages are infrequent, NAP Colombia remains strong not only in terms of traffic exchanged (18 Gbps during peak times and growing at 5% annually) but also in terms of membership, accounting for 95% of Colombian Internet subscribers.

[10] Estimate based on personal interviews. See also Mejia, Fabian, "NAP.EC e IPv6", presented at *IPv6 en Ecuador*, June 6, 2012. Available at 02 presentacion nap_ec ipv6_2012-06-06.pdf.

[11] For a discussion see Galperin (2013).

[12] See also Seoane, Hernan "Red Nacional NAPs CABASE", presented at the PTT Forum 8, 24 November 2014. Available at ptt.br/pttforum/8/doc/04-2014-11_Nic_BR.ppt.

Table 3
Cost breakdown estimate for a small ISP in Argentina, 2014.

	Traffic (in %)	Contracted capacity (in Mbps)	Cost per Mbps (in USD)	Baseline scenario (no IXP)	Alternative scenario (with IXP)
International traffic	40	80	60	–	$4800
Local traffic	25	50	15	–	$750
CDNs	35	70	1	–	$70
Membership costs	–	–	–	–	$100
Total	100	200		$12,000	$5720

Source: CABASE and personal interviews.

Because of its privileged geographical location and adequate supply of international bandwidth capacity, latency in the routes to the United States is a relatively limited concern for Colombian operators, with estimates of about 45 ms from the capital city Bogota to Miami. Yet this compares to a latency of 3 ms for local traffic, which provides a strong rationale for hosting content locally. Interestingly, latency is significantly higher in routes from Colombia to other Latin American countries such as Brazil (150 ms) and Argentina (190 ms), which illustrates the deficiencies in regional connectivity between countries in the continent (see Garcia-Zaballos et al., 2011).[13]

In order to obtain more accurate estimates of the quality improvements that result from the presence of a local IXP, we deployed network measurement probes in the two largest Bolivian cities, La Paz and Santa Cruz. The probes measured two basic parameters that affect QoS: latency (measured in Round Trip Time, or RTT) and distance (measured in number of hops). Measurements were taken over a 8-month period immediately following the launch of PIT Bolivia, the country's first IXP, in November 2013 (it is worth recalling that ISPs were mandated by law to exchange local traffic at PIT Bolivia). The probes actively generated local traffic (i.e., both source and destination IP address assigned to Bolivia) by executing traceroutes to a large sample of Bolivian IP addresses. The measurements obtained were divided into the following three categories: (a) *IXP routes* (i.e., routes that include an IP address assigned to PIT Bolivia); (b) *P2P routes* (i.e., routes that do not pass through PIT Bolivia but do not include foreign servers); and (c) *International routes* (i.e., routes that include a non-Bolivian IP address).[14]

The results are presented in Fig. 2 (RTT) and Fig. 3 (number of hops). They suggest that PIT Bolivia has significantly reduced latency for routes originating and terminating in Bolivia. In particular, the median RTT for *International routes* is 3.97 times larger than for *IXP routes.* In other words, localizing the exchange of IP traffic between Bolivian network operators has reduced latency by a factor of 4. Similarly, the median number of hops for *International routes* is 1.45 larger than the median for *IXP routes* (as expected P2P routes are even shorter). The variance is also smaller for *IXP routes*, which suggests both shorter and more reliable paths. Overall, the evidence consistently suggests a significant positive impact of PIT Bolivia on QoS parameters in local routes.

4.3. Impact on small and medium-sized markets

One of the biggest challenges for Internet growth in Latin America in the next decade is the mitigation of regional imbalances in basic infrastructure development. As many studies have shown, such imbalances both reflect and reproduce long-term economic and social disparities that characterize the region, while the impact of universal service programs designed to alleviate them has been modest at best (Barrantes, 2011; Stern, 2009). As Galperin and Bar (2007) argue, small and medium-size telecommunications operators make an important contribution to mitigate such regional disparities, as they typically provide services in less populated and more isolated areas of little interest to larger firms.

IXPs are vital to the development of small and medium-size ISPs for the several of the reasons already noted. They are critical for aggregating traffic in smaller markets, allowing network operators to negotiate better transit prices, while also making local caching or peering more attractive for content providers and other larger networks. IXPs also provide incentives for members to invest in switching equipment and logical resources, for example by requiring that members run their own ASN (Autonomous System Number).[15] Further, IXPs provide incentives for small and medium-sized ISPs to invest in their own physical infrastructure in order to transport traffic to a neutral point where it can be exchanged with other networks. By controlling their own infrastructure, local ISPs are able to climb the so-called "ladder of investment" (Cave, 2006) and compete at a higher level in the Internet value chain. Lastly, IXPs play a critical role as a knowledge hub for operators with very limited ability to invest in R&D or training.

The case of the PTT Metro initiative in Brazil illustrates the dynamics of cooperative peering in small and medium-size markets. Until 2003 only three cities in Brazil (the fifth largest country in the world by area) had an IXP in operation. This

[13] Source: CCIT (2012). Similar results are reported by de León (2012).
[14] For a detailed discussion on measurement methodology and results see Carisimo et al. (2015).
[15] An ASN (Autonomous System Number) refers to a pool of IP addresses which are under the control of a network operator and thus share a routing policy to the Internet. As O'Flaherty and Woodcock (2011) argue, without an ASN an ISP lacks the ability to define its own routing policies, effectively becoming a simple reseller of services operated by its upstream transit provider.

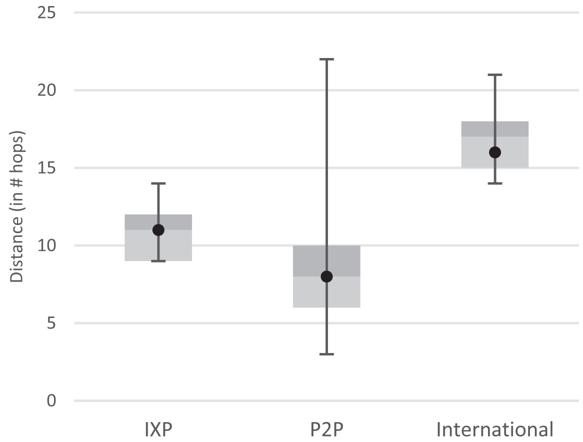

Fig. 2. Distance by route category (PIT Bolivia). Source: own measurements.

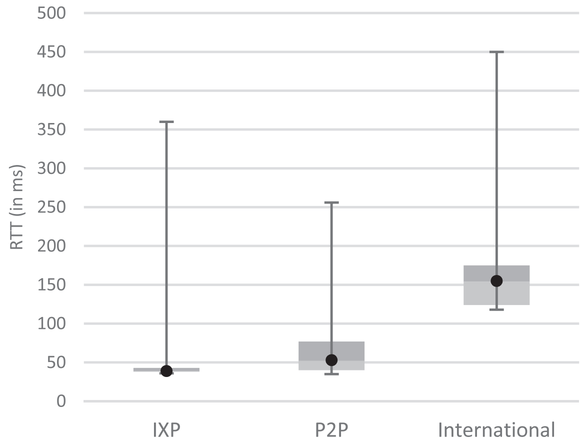

Fig. 3. Latency by route category (PIT Bolivia).

resulted in significant regional and international tromboning of local traffic, negatively affecting both costs and QoS outside the larger urban areas. In 2004 the Comitê Gestor da Internet (CGI), a multistakeholder body responsible for coordinating and promoting the development of the Internet in Brazil (including administration of the .br domain name), launched an initiative called PTT Metro to create IXPs in small and medium-size cities across the country. As of 2015 there were 25 IXPs in operation, covering 18 of Brazil's 26 states (see Table 4).

As Cavalcanti (2011) indicates, the newly established IXPs have improved network performance and created critical redundancy in routes for operators located in smaller markets. This is the case of SERCOMTEL, a medium-size operator based in the city of Londrina (population 766,000). Before the initiative, much of SERCOMTEL's traffic was transported over a single transit agreement with an upstream provider. By establishing a presence at three PTT Metro locations (São Paulo, Curitiba and Londrina itself), SERCOMTEL has not only significantly increased the number of its peers but also balanced traffic more evenly over different routes. Critically, by peering at PTT Metro São Paulo, it has established a more direct route to key content providers such as Google. Average latency on its routes has since dropped from 50 ms to 10 ms.[16]

Table 4 also suggests that there is no clear correlation between market size and IXP scale (measured both in number of peers and traffic). Some IXPs thrive in smaller markets such as Londrina (pop. 766,000) while others remain marginal in much larger markets such as Manaus (pop. 1.8 M) or Recife (pop. 1.5 M). Much depends on the specific conditions of each local market, and the commitment of key network operators from the private and public sectors. In particular, the participation of local government agencies and other public institutions (e.g., universities) is critical to jump-start IXPs in small and medium-sized markets. Economies of scale are also critical for management and operations. As the case of PTT Metro illustrates, several of the smaller IXPs would not be viable without technical and operational support from CGI.

[16] Source: personal interviews. See also Barros Tonon, R. (2011), "Beneficios de los PTT para los Pequeños y Medianos Operadores en Brasil". Presented at NAPLA, May 15–20, 2011.

Table 4
A snapshot of the PTT Metro initiative (location, members and average traffic) in 2015.

City	State	Pop. (in 000s)	# Peers	Traffic (Mbps)
Belem	PR	1.392	14	498
Belo Horizonte	MG	2.375	36	2700
Brasilia	DF	2.562	32	2970
Campina Grande	PB	383	11	433
Campinas	SP	1.080	37	2660
Cuiaba	MT	575	9	1
Caxias do Sul	RS	410	5	76
Curitiba	PA	1.746	38	16,940
Florianopolis	SC	408	42	1200
Fortaleza	CE	2.447	28	1190
Goiania	GO	1.301	25	947
Lajeado	RS	71	7	0.25
Londrina	PA	766	33	1540
Manaus	AM	1.802	7	9
Maringa	PR	390	21	400
Natal	RN	806	12	851
Porto Alegre	RS	1.409	64	12,120
Recife	PE	1.536	16	889
Rio de Janeiro	RJ	6.323	71	29,300
Salvador	BA	2.676	47	1520
São Carlos	SP	238	3	0.25
São Jose Campos	SP	615	13	580
São Jose Rio Preto	SP	425	12	26
São Paulo	SP	11.244	+300	394,000
Vitoria	ES	320	23	616

Source: CGI (www.cgi.br) and IBGE (www.ibge.gov.br).

5. Conclusion

In the past two decades the Internet has evolved from a small-scale research initiative into a large-scale communications platform used by several billions. Despite this transformation, cooperation between independent network operators remains at the core of its architecture. In particular, settlement-free peering agreements have expanded from the Internet's core towards its edges. As shown, the number and traffic volume of IXPs in developing regions continue to expand. In Latin America, the bulk of the growth is explained by IXPs run as non-profit organizations governed by its own members. Both theoretical arguments and empirical evidence demonstrate how these IXPs have had a significant positive impact on Internet growth in the region.

The evidence from Latin America also suggests that there are several enabling factors for IXPs. First and foremost is a competitive telecommunications market that facilitates entry and promotes competition in domestic transport. Unless transport prices are competitive, local ISPs will have few incentives to invest in infrastructure and exchange traffic at local facilities. In several countries in the region, this basic condition is yet to be met. Second, governments can play a catalyzing role by providing political support for the establishment of local traffic exchange facilities. This is particularly true in countries where the state controls the legacy telecoms operator, as is the case in several of the least developed Internet markets in Latin America (e.g., Bolivia and Paraguay). Since incumbent operators typically have fewer incentives to peer at IXPs (particularly if a multilateral peering policy is enforced), government support is often critical for IXPs to succeed.

However, heavy-handed government regulation of IXP operations is ill-advised. As the case studies show, IXPs require flexibility to adapt to local market conditions and a rapidly changing interconnection environment. The case of Bolivia is particularly revealing, as the government's mandate to interconnect has been met with distrust from private operators, despite evidence that PIT Bolivia has helped improve QoS. A key concern has been the role of the state-owned operator ENTEL in the technical operation of PIT Bolivia. Overall, the cases examined suggest that, while governments have an important role to play in facilitating and promoting cooperative peering, policy mechanisms must guarantee both neutrality and efficiency in IXP operations. In other words, policy initiatives that seek to tip private incentives in favor of cooperative peering at the local level have proven more effective than detailed regulatory mandates of IP interconnection.

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