

# Using Tuangou to Reduce IP Transit Costs

Ignacio Castro, *Student Member, IEEE*, Rade Stanojevic, *Member, IEEE*, and Sergey Gorinsky, *Member, IEEE*

**Abstract**—A majority of Internet service providers (ISPs) support connectivity to the entire Internet by transiting their traffic via other providers. Although the transit prices per megabit per second (Mbps) decline steadily, the overall transit costs of these ISPs remain high or even increase due to the traffic growth. The discontent of the ISPs with the high transit costs has yielded notable innovations such as peering, content distribution networks, multicast, and peer-to-peer localization. While the above solutions tackle the problem by reducing the transit traffic, this paper explores a novel approach that reduces the transit costs without altering the traffic. In the proposed Cooperative IP Transit (CIPT), multiple ISPs cooperate to jointly purchase Internet Protocol (IP) transit in bulk. The aggregate transit costs decrease due to the economies-of-scale effect of typical subadditive pricing as well as burstable billing: Not all ISPs transit their peak traffic during the same period. To distribute the aggregate savings among the CIPT partners, we propose Shapley-value sharing of the CIPT transit costs. Using public data about IP traffic and transit prices, we quantitatively evaluate CIPT and show that significant savings can be achieved, both in relative and absolute terms. We also discuss the organizational embodiment, relationship with transit providers, traffic confidentiality, and other aspects of CIPT.

**Index Terms**—Burstable billing, cost benefit analysis, economies of scale, Internet Protocol (IP) networks, Shapley value, transit.

## I. INTRODUCTION

THE INTERNET ecosystem involves thousands of Internet service providers (ISPs) linked in a more or less hierarchical manner to support universal connectivity of Internet users. Only a handful of huge ISPs can access the entire Internet without paying anyone for the reachability. For the vast majority of the other ISPs, the universal connectivity comes at the price of Internet Protocol (IP) [41] transit: Typically, a smaller ISP pays a larger provider for the traffic transited in both directions of the link between the two ISPs.

Transit costs are a significant part of the overall costs of ISPs [10], [32], [43] because the decline of transit prices *per megabit per second (Mbps)* is accompanied by the fast growth of transit traffic [33]. The problem of reducing the IP transit costs has attracted notable solutions of Internet exchange points (IXPs) [1], [6], [23], IP multicast [7], [11], [21], [35], [36], content distribution networks (CDNs) [59], peer-to-peer (P2P)

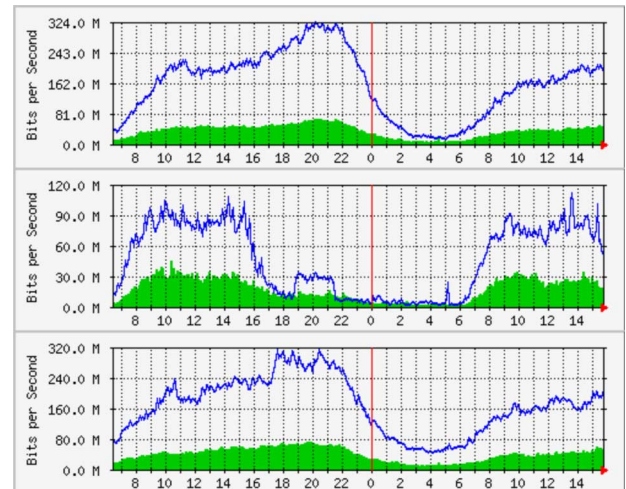


Fig. 1. Demand statistics for partners (*top*)  $P_1$ , (*middle*)  $P_2$ , and (*bottom*)  $P_3$  in the motivating example. The  $x$ -axes are in hours; the  $y$ -axes are in *Mbps*. The filled areas depict the upstream traffic; the lines represent the downstream traffic.

localization [15], and traffic smoothing [42], [45], [54]. One property that these proposals share is their objective to reduce the amount of traffic that traverses transit links. Intuitively, the less traffic of an ISP that flows through those links, the lower the cost is for the ISP.

This paper proposes *Cooperative IP Transit (CIPT)*, a different approach to reducing the cost of IP transit. Instead of altering the traffic that flows through the transit links, CIPT reduces the price of transit *per Mbps*: By jointly purchasing the IP transit, two or more ISPs reduce the transit prices per Mbps for *each* ISP involved in the CIPT.

Tuangou<sup>1</sup> (group buying) has been highly successful in other domains [46]. While tuangou succeeds primarily due to subadditivity of prices [12], [33], [69], the benefits of CIPT depend also on burstable billing [27], different methods to account for bidirectional traffic, and other complex factors.

To illustrate the CIPT concept, Fig. 1 plots real traffic profiles of three ISPs. If the ISPs form a CIPT and purchase transit jointly, the total cost is smaller than when purchasing it separately because: 1) transit billing is burstable, i.e., the buyer is billed for the peak of its traffic; because the peaks of the traffic of the ISPs are not completely coincident, the peak of the combined traffic is smaller than the sum of the separate peaks; 2) transit prices are subadditive, i.e., prices *per Mbps* decrease as the purchased amount increases. Consequently, the traffic aggregation enables CIPT to reduce costs of its partners.

The novelty of CIPT in the Internet ecosystem lies in the cooperative essence of the arrangement. While CIPT reduces

<sup>1</sup>Tuangou (pronounced “twangoo”), a term originating in China, loosely translates as group buying (<http://en.wikipedia.org/wiki/Tuangou>).

Manuscript received January 31, 2013; accepted July 30, 2013; approved by IEEE/ACM TRANSACTIONS ON NETWORKING Editor R. Teixeira.

I. Castro is with Institute IMDEA Networks, Madrid 28918, Spain, and also with the Internet Interdisciplinary Institute (IN3), Open University of Catalonia, Barcelona 08018, Spain (e-mail: ignacio.decastro@imdea.org).

R. Stanojevic was with Institute IMDEA Networks, Madrid 28918, Spain. He is now with Telefonica I+D, Barcelona 08019, Spain (e-mail: rade@tid.es).

S. Gorinsky is with Institute IMDEA Networks, Madrid 28918, Spain (e-mail: sergey.gorinsky@imdea.org).

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TNET.2013.2278236

costs by transit traffic aggregation, the latter is common in the Internet. Most transit providers are transit resellers that profit from lower rates resulting from transit aggregation. As early as in the 1990s, The Little Garden (TLG) [48] pooled traffic of small customers together to obtain cheaper transit rates. Government-promoted IXPs also lower transit costs through national transit traffic aggregation, e.g., in Bahrain [9], [63] and other developing countries [3], [34]. CIPT is substantially different from previous transit-aggregation schemes in the following aspects:

- cooperation of transit buyers;
- mechanisms for distribution of the benefits of transit aggregation.

Beyond the new application of *tuangou* in the domain of IP transit, a major contribution of this work lies in its measurement and evaluation methods. Relying on real interdomain traffic and transit pricing, this paper estimates the gains from CIPT. We also propose Shapley value as a basis for sharing the gains among the CIPT partners so as to provide each partner with a strong economic incentive for the cooperation. Our evaluation of the aggregate and individual gains involves collection of the visual traffic statistics from six public IXPs with 264 participating ISPs, transformation of the visual images into a numeric format, and public-data validation of the property that peering and transit traffic have similar temporal profiles. Our analysis suggests that the expected relative savings of CIPT are in the range of 8%–56% for the IXP-wide coalitions; in absolute terms, each of the partners may expect annualized savings from US \$1000 for very small ISPs to several hundred thousand dollars for the few large ISPs. We also show that much smaller coalitions, with a half a dozen of members, can offer close-to-maximum savings. The main contributions of our paper are as follows.

- We propose CIPT, a simple cooperative strategy to reduce costs by purchasing IP transit jointly.
- We show that CIPT can be modeled as a cooperative game and that Shapley value provides an intuitive mechanism for cost sharing in CIPT.
- We use public IXP data to infer the traffic time series for several hundred (mostly regional and national) ISPs and use this information to assess the potential cost benefits of CIPT.

While our results on the CIPT cost reduction validate the potential of CIPT to become a new viable element of the Internet ecosystem, the practical viability of CIPT also depends on other strategic and organizational issues. For example, if two ISPs are already engaged in a transit relationship, they are unlikely to agree on buying IP transit jointly from a third party. Also, the transit provider can strategically respond to CIPT by charging the coalition at higher prices per Mbps than the prices offered to an individual ISP. On the other hand, big transit providers might strategically accept CIPT to squeeze out smaller transit providers. By aggregating transit traffic, CIPT might become an attractive customer for large transit providers bypassing transit resellers. It is quite possible that CIPT will not grow into the dominant mechanism for IP transit cost reduction. On the other hand, earlier success in cost reduction via transit aggregation [3], [9], [34], [48] suggests that CIPT is certainly feasible and can gain a broad presence in the Internet

TABLE I  
IP TRANSIT PRICING RATES

Committed Data Rate, <i>Mbps</i>	Price per <i>Mbps</i> per month
10	\$25
50	\$15
100	\$10
1000	\$5
10000	\$4

ecosystem, from small Web sites in a hosting facility to the level of nationwide ISPs. Data-driven assessment of all these additional issues lies beyond the scope of this paper. Similarly, while we propose Shapley value as a means for cost sharing in CIPT, evaluation of alternative solutions to CIPT cost sharing is a topic for future work.

The rest of the paper is structured as follows. Section II reviews the particulars of IP transit pricing and illustrates the CIPT potential with a simple numeric example. Section III formulates CIPT as a cooperative game. Section IV explores CIPT cost sharing. Section V evaluates CIPT based on the public data. Section VI discusses implementation and deployment issues. Section VII analyzes strategic aspects of CIPT. Section VIII presents related work. Finally, Section IX sums up the paper and its contributions.

## II. BACKGROUND AND MOTIVATION

The geographic location significantly affects the cost of IP transit. The IP transit prices per *Mbps* per month range usually from \$5 to \$100 (we use \$ or US\$ to refer to US dollars throughout the paper): The wholesale IP transit is typically priced under \$10 per *Mbps* in most European and North American hubs, but can exceed \$100 per *Mbps* in Australia, Latin America, and other remote regions of the Internet [3], [33].

Regardless of the geographic location, IP transit is subject to economies of scale and is priced subadditively: The prices per *Mbps* are smaller for larger quantities of IP transit [33]. Table I presents real (as of January 2011) transit pricing rates of a middle-size transit provider in North America. The table reports the prices for different levels of committed data rate (CDR), the minimum amount charged by the provider. For example, an ISP with IP transit needs of 300 *Mbps* commits at the 100-*Mbps* CDR level and pays pro rata \$3000 to the transit provider, but an ISP with IP transit needs of 700 *Mbps* finds it more cost-effective to commit at the 1000-*Mbps* CDR level and pays \$5000.

Burstable billing is another important aspect of IP transit pricing [27], [54]. To calculate the IP transit cost, the most commonly used method is to calculate the *peak* usage (typically through the 95th-percentile rule [27], [54]), and then the price function  $f$  is applied to the observed *peak* to calculate the resulting payment. The *peak* value is usually calculated separately for the upstream and downstream directions, and either sum or maximum of the two is used for billing. We refer to these two pricing models as sum and max models. Intuitively, the max model offers a larger opportunity for savings in cooperation because two ISPs with their traffic peaks in opposite directions can mutually benefit from the less utilized directions

of each other. Consequently, results for the sum model can be considered as a conservative estimate of CIPT gains (Fig. 10 in the Appendix confirms this intuition).

To illustrate the potential of CIPT, we consider a simple scenario of three partners<sup>2</sup>  $P_1$ ,  $P_2$ , and  $P_3$  interested in purchasing IP transit from the same provider. We assume the transit pricing rates as in Table I, 95th-percentile burstable billing, sum model of accounting for bidirectional traffic, and traffic profiles plotted in Fig. 1.

If the three partners purchase the IP transit separately, the individual traffic peaks (computed as the sum of the peaks in both directions) of  $P_1$ ,  $P_2$ , and  $P_3$  are at 379, 130, and 362 *Mbps* respectively, and each of the partners commits at the 100-*Mbps* CDR level. Thus, partners  $P_1$ ,  $P_2$ , and  $P_3$  pay respectively \$3790, \$1300, and \$3620 with the aggregate transit cost of \$8710.

On the other hand, if  $P_1$ ,  $P_2$ , and  $P_3$  use CIPT to buy the IP transit together, their aggregate peak traffic is 712 *Mbps*. By committing at the 1000-*Mbps* CDR level, the CIPT pays \$5000. Thus, the cooperation reduces the aggregate transit cost of the partners by \$3710, or 43%. This significant cost reduction comes from two different sources.

- 1) Burstable billing: The 712-*Mbps* peak of the aggregate traffic is lower than the 871-*Mbps* sum of the individual traffic peaks; hence, the aggregate transit cost would decrease even if the pricing function were additive.
- 2) Subadditive pricing: The upgrade from the 100-*Mbps* CDR level to the 1000-*Mbps* one provides a lower price per *Mbps* and thereby reduces the aggregate transit cost even further.

### III. COOPERATIVE IP TRANSIT

In Section I, we sketched the main idea of the CIPT. This section provides more details, describes the concept of cooperative (or coalitional) games, and models CIPT as a cooperative game.

CIPT refers to any cooperative mechanism in which two or more subjects purchase the IP transit jointly as a means for cost reduction. The subject interested in CIPT can be any Internet entity that buys IP transit; such entities include Web sites and hosting providers, as well as access, nonprofit, and content ISPs.

The main incentive for forming a CIPT coalition is financial: Each partner reduces its individual IP transit bill. The typical IP transit pricing makes it virtually impossible for a set of potential partners to increase their aggregate transit cost by buying the IP transit jointly. However, CIPT needs a reasonable mechanism to distribute the aggregate cost savings among all the CIPT partners. Furthermore, the aggregate and individual IP transit costs of the CIPT partners strongly depend on a number of factors such as the IP transit pricing function, number of partners, their size, and temporal patterns of their traffic demands.

#### A. CIPT as a Cooperative Game

Formally, a cooperative game is characterized by set  $\mathcal{N}$  of involved players and a cost function that maps the partitive<sup>3</sup> set

<sup>2</sup>We interchangeably use terms partner and player to refer to any ISP, hosting provider, or any other entity interested in purchasing IP transit.

<sup>3</sup>For set  $\mathcal{N}$ , the partitive set of  $\mathcal{N}$  is the set of all subsets of  $\mathcal{N}$  and is usually denoted as  $2^{\mathcal{N}}$ .

of  $\mathcal{N}$  to a cost value:  $c : 2^{\mathcal{N}} \rightarrow R$ . In the context of CIPT, set  $\mathcal{N}$  is the set of subjects interested in purchasing IP transit. The cost function maps an arbitrary subset  $S \subset \mathcal{N}$  to the cost of the IP transit that the coalition of players from  $S$  would pay. An important property of the IP transit model is that the price per *Mbps* is a nonincreasing function of the *peak* due to the subadditive nature of the pricing model.

CIPT is formed by a set of  $N$  partners. Each partner  $i$  of the CIPT has upstream and downstream IP transit traffic demands represented respectively by time series  $u_i(t)$  and  $d_i(t)$  where  $i \in \{1, 2, \dots, N\}$ , and time  $t$  is measured in fixed-size time intervals with a typical interval duration of 5 min. The cost that subject  $i$  pays for the transit, without participation in CIPT, is the function of these demand series

$$C_i = F(u_i(\cdot), d_i(\cdot)).$$

After bundling of  $N$  subjects, the aggregate upstream/downstream demands are the sum of the corresponding individual demands

$$u(t) = \sum_{i=1}^N u_i(t) \text{ and } d(t) = \sum_{i=1}^N d_i(t)$$

and the aggregate cost of the IP transit is

$$C = F(u(\cdot), d(\cdot)).$$

The 95th-percentiles of the upstream ( $peak^{(up)}$ ) and downstream ( $peak^{(down)}$ ) traffic are calculated, and the *peak* value used for billing is either the sum or max of these two values, as described in Section II. The transit cost of the coalition of these  $N$  players is then

$$C = F(u(\cdot), d(\cdot)) = f(peak)$$

where  $f$  is the pricing function decided by the IP transit provider. This pricing function is typically subadditive, Table I provides an example of such pricing function.

Additionally, for virtually any real-world subjects interested in purchasing IP transit, the peak traffic of the union of two subjects is smaller than the sum of the peaks of these two subjects. In case of measuring the peak as the maximal traffic, this is an obvious consequence of the fact that the maximum of the sum of two nonnegative functions (over the same domain) is not greater than the sum of the maximums of these two functions. If the peak is measured through the 95th-percentile method, there may be some irregular cases<sup>4</sup> in which the sum of the 95th-percentiles is smaller than the 95th-percentile of the union of the traffic of the two subjects. Nevertheless, these situations are extremely unlikely to happen in regular setups. We demonstrate this in Fig. 2 by plotting the cumulative distribution for the ratio of the 95th-percentile of the union to the sum of the 95th-percentiles across *all* the pairs of ISPs at Budapest Internet Exchange (BIX) in both sum and max models. BIX and several other IXPs publish traffic statistics that each of

<sup>4</sup>For example, two subjects consuming 100 *Mbps* 4% of the time each—one in the morning, the other over night—and using 1 *Mbps* the remaining 96% of the time will have their 95th-percentile equal to 1 *Mbps*, while their union would have 95th-percentile equal to 100 *Mbps*.

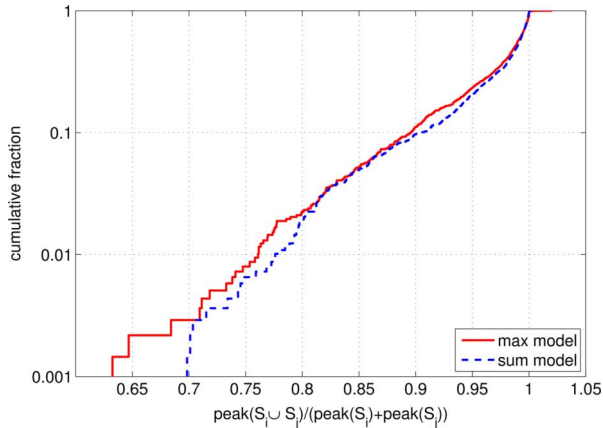


Fig. 2. Distributions for the ratio of the 95th-percentile of the union to the sum of the 95th-percentiles across all the pairs of ISPs at Budapest Internet Exchange.

their members (mostly regional ISPs) exchanges at the IXP, and this information represents valuable and useful proxy for estimating the traffic patterns (volume, peak-hour, peak-to-valley ratio, up/downstream traffic ratio, etc.) for the involved ISPs.

*Observation 1:* The traffic patterns of subjects interested in CIPT are such that for (almost) all pairs of coalitions  $S_1$  and  $S_2$  of these subjects, the peak value of the union of the two coalitions is smaller than the sum of the peak values of these two coalitions.

As we elaborate above, Observation 1 is intuitive and can be empirically validated for available data of traffic patterns. From now on, we assume that subjects involved in CIPT are such that this observation is true. In that case, cost function  $c(\cdot)$  is indeed subadditive

$$c(S_1) + c(S_2) \geq c(S_1 \cup S_2), \quad \text{for any } S_1, S_2 \subset \mathcal{N}. \quad (1)$$

Hereby, virtually always the overall IP transit cost of CIPT is strictly smaller than the sum of individual IP transit costs of all involved players

$$\rho = \frac{C}{\sum_{i=1}^N C_i} < 1.$$

The relative savings  $(1 - \rho)$  of the CIPT are influenced by several factors, with the two dominant being: 1) the subadditivity of the price function, and 2) burstable billing through the 95th-percentile method. Namely, the subadditive pricing leads to savings for the involved players because prices (per *Mbps*) are lower for larger quantities. Additionally, with the burstable billing, when two or more players have nonoverlapping peak hours, their coalition would have the peak value strictly smaller than the sum of the peak values of the involved players. While players that serve similar user bases have similar temporal usage patterns (e.g., residential networks peak in evening hours, government/academic networks peak in early afternoon), the networks of different types experience their peaks in times that are far apart, which in turns allows for additional savings in top of bundling and buying-in-bulk.

*Comment 1:* While this paper focuses on IP transit, the CIPT concept is relevant and straightforwardly applicable to cost reduction in other Internet business domains, such as IP transport and IXPs. As with IP transit, purchase of an IP transport link between two remote locations is also costly and subject to sub-additive pricing. Multiple ISPs that need to reach the same remote location (e.g., an IXP) can reduce their IP transport costs by jointly buying a single IP transport link. Nonprofit IXPs constitute another instance of the CIPT concept: Instead of buying IXP services from a third-party commercial provider, multiple ISPs can form a nonprofit IXP, cooperatively pay for the IXP infrastructure, and thereby reduce their peering costs.

#### IV. COST SHARING IN CIPT

A key question in any cooperation scheme created for cost reduction reasons is how to split the aggregate costs of cooperation. As we saw in Section III-A, CIPT can be abstracted as a cooperative game that puts us in a position to use the rich set of analytic tools for solving the problem of cost sharing. There are many solution concepts for cost sharing in cooperative games, including the core, kernel, nucleolus, and Shapley value [74]. While other solution concepts have attractive features, in the context of CIPT we find particularly appealing to use the Shapley value since it has several distinct important properties, i.e., the Shapley value: 1) *exists* for any cooperative game and is *uniquely* determined; 2) satisfies basic *fairness* postulates [65], [74]; and 3) is *individually rational*, i.e., each player in CIPT receives a lower Shapley value cost than what it would be if it did not participate in CIPT. One potential deficiency of the Shapley value is that in general it is computationally hard to calculate it exactly. However, state-of-the-art techniques provide simple and accurate methods for Shapley value approximation, as discussed in Section IV-B.

##### A. Shapley Value: Definition

For a cooperative game defined over set  $\mathcal{N}$  of  $N$  players and each subset (coalition)  $S \subset \mathcal{N}$ , let  $c(S)$  be the cost of coalition  $S$ . Thus, if coalition  $S$  of players agrees to cooperate, then  $c(S)$  determines the total cost for this coalition.

For given cooperative game  $(\mathcal{N}, c(\cdot))$ , the Shapley value is a (unique) vector  $(\phi_1(c), \dots, \phi_N(c))$  defined below, for sharing the cost  $c(\mathcal{N})$  that exhibits the coalition of all players. It is a “fair” cost allocation in that it satisfies four intuitive properties: efficiency, symmetry, additivity, and null-player; see [65] and [74] for exact definitions of these properties and more details. The Shapley value of player  $i$  is precisely equal to  $i$ ’s expected marginal contribution if the players join the coalition one at a time, in a uniformly random order. Formally, it is determined by

$$\phi_i(c) = \frac{1}{N!} \sum_{\pi \in \mathcal{S}_N} (c(S(\pi, i)) - c(S(\pi, i) \setminus i)) \quad (2)$$

where the sum is taken across all permutations (or arrival orders),  $\pi$ , of set  $\mathcal{N}$  and  $S(\pi, i)$  is the set of players arrived in the system not later than  $i$ . In other words, player  $i$  is responsible for its marginal contribution  $c(S(\pi, i)) - c(S(\pi, i) \setminus i)$  averaged

TABLE II  
BASIC STATS ON THE USED IXPs

IXP	acronym	# of members	peak (Gbps)	average (Gbps)	95th-pct effect		subadditive effect		skewness
					sum	max	sum	max	
Neutral IX (Prague)	NIX	54	116	76	4.3%	29.1%	95.7%	70.9%	0.76
Slovak IX	SIX	52	42	23	15.4%	44.9%	84.6%	55.1%	0.27
Israeli IX	IIX	17	2.1	1.38	14.3%	40.6%	85.7%	59.4%	0
Finnish IX	FICIX	25	32	19	6.7%	23.1%	93.3%	76.9%	0.48
InterLAN (Bucharest)	InterLAN	63	22	11	14.3%	37.8%	85.7%	62.2%	0.12
Budapest IX	BIX	53	152	92	3.6%	27.8%	96.4%	72.2%	0.84

across all  $N!$  arrival orders  $\pi$ . Note that the Shapley value defined by (2) indeed satisfies the *efficiency* property

$$\sum_{i \in \mathcal{N}} \phi_i(c) = c(\mathcal{N}).$$

### B. Estimation of the Shapley Value in CIPT

While the Shapley value can be computed in a rather straightforward manner using (2), it is not practically feasible to employ (2) for  $N > 30$ . A number of methods have been suggested for accurate estimation of the Shapley value, and in this paper we use a simple Monte Carlo method [47] as follows.

Instead of calculating the exact Shapley value as the average cost contribution across all  $N!$  arrival orders, we estimate the Shapley value as the average cost contribution over set  $\Pi_k$  of  $K$  randomly sampled arrival orders

$$\hat{\phi}_i(c) = \frac{1}{K} \sum_{\pi \in \Pi_k} (c(S(\pi, i)) - c(S(\pi, i) \setminus i)). \quad (3)$$

Parameter  $K$  determines the error between the real Shapley value and its estimate: The higher  $K$ , the lower the error. Thus, basically, one can control the accuracy of the estimator by increasing the number of sample permutation orders. We observe in our datasets of traffic demands that the value of  $K = 1000$  provides errors of under 1% across all the CIPT players, and in the rest of the paper we use  $K = 1000$  for the computation of the Shapley value.

## V. EVALUATION

In this section, we quantify various factors that impact CIPT by using traffic information from 264 (mainly national and regional) ISPs. In Section V-A, we describe the dataset and pricing model(s). In Section V-B, we evaluate the potential savings of CIPT on countrywide (IXP-wide) collaborations and show that significant savings could be expected both in relative and absolute terms. In Section V-C, we augment this analysis by empirically showing that even small single-digit coalitions can yield close-to-optimal savings, by demonstrating a law of diminishing returns for the savings as a function of the coalition size. Section V-D analyzes the per-player savings and shows somewhat expectable trends that the larger the player is, the larger are its absolute savings, but the smaller its relative savings are. Finally, in Section V-E, we analyze the effects of collaboration between geo-diverse players and present an analytical upper bound on the savings as a function of the time difference in their peak-hour periods.

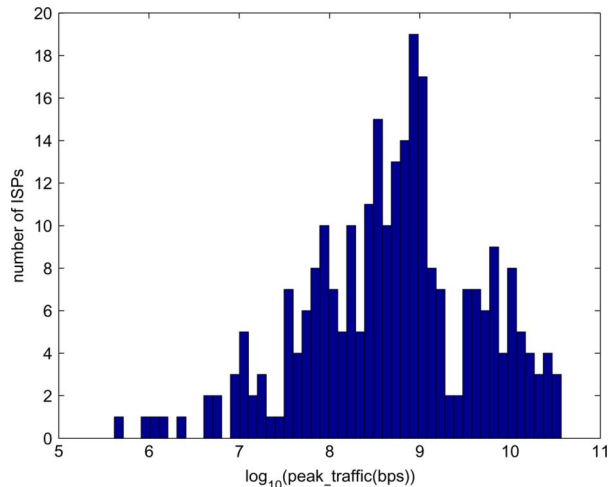


Fig. 3. Distribution of the peak traffic rates across all 264 ISPs. Median: 560 Mbps; mean: 2.9 Gbps.

### A. Dataset Description

Although data for the traffic patterns of many ISPs are often kept confidential, some public IXPs report upstream and downstream demand time series for the traffic exchanged by every member of the IXPs. Those that do it are listed in Table II. These traffic statistics data are typically given in the form of mrtg images [58], similar to those shown in Fig. 1. Overall, we collected the information for 264 ISPs, with the traffic peak distribution as shown in Fig. 3. While the information about the traffic exchanged at the public IXPs is obviously a valuable piece of information, it is not straightforward how to use this information to estimate the transit usage of the ISPs. In Section V-A.2, we use a small set of ISPs that make their detailed traffic information public to show that the IXP related traffic is a good proxy for estimating the transit part of the interdomain traffic, at least for some ISPs. Before that, we elaborate on the data collection.

1) *Dataset Collection*: We started by manually inspecting the Web pages of medium-size and large IXPs at [30]. A majority of these IXPs publish their aggregate traffic statistics, summed across all the members, but some also make public the detailed traffic statistics of their members. We identified several IXPs that do so. Table II lists them. We then crawled the Web sites of these IXPs and collected per-member traffic information. These per-member traffic data are typically given in the form of visual images, similar to those in Fig. 1, produced as the outputs of the standard tools for traffic visualization: mrtg/rrdtool [58]. To convert the information into a numeric form, we built a piece of software that takes as input a mrtg/rrdtool image and outputs the numeric array representing

the upstream/downstream traffic time series. This operation of transforming the .png images to numeric data required serious effort in the domain of optical character and function recognition. The raw visual data, numeric data, and code for transforming the mrtg/rrdtool images into the numeric format can be found at [16].

2) *From IXP Data to IP Transit Traffic*: Most ISPs consider the data of their networks as confidential and are reluctant to share them with third parties. However, some ISPs publicly share large amounts of operational information. In particular, several European ISPs serving academic institutions have publicly shared on their Web sites detailed pictures of both their network infrastructure and utilization of their networks. Those that we identified are HEANET (Ireland) [38], SANET (Slovak Republic) [64], CESNET (Czech Republic) [13], and GRNET (Greece) [37]. We inspected the peering and transit traffic for those four ISPs and found that the peering traffic pattern is a good first-order indicator of the transit traffic. In those four ISPs, peering corresponds to 35%–40% of the total traffic, with the remaining 60%–65% being transit. Additionally, we observe that peering and transit traffic follow very similar temporal patterns: Their growth and decay periods coincide, they peak at the same time, have similar peak-to-valley ratios, etc.; see the Appendix for more details. In some sense, such behavior is not very surprising: Given that the demand is predominantly created by humans, both transit and peering traffic demand are driven by the same end-user activities.

Consequently in our analysis, we approximate the transit traffic of ISPs (belonging to corresponding IXPs) with their peering traffic (information that is publicly available) multiplied by a factor  $\gamma$  that determines the relative weight of the transit versus peering traffic. In Section V-B, we describe expectable savings of CIPT for  $\gamma \in [0.5, 4]$ . However, in Sections V-C–V-E (which analyze the cost-sharing, coalition size, and geo-diversity), we fix  $\gamma$  at 1.5, which corresponds to the transit/peering traffic ratio of 60/40 suggested by our analysis in the Appendix for medium-size European countries with a single dominant IXP (the case of our six IXPs).

While this approximation is rather crude, it nevertheless captures the main features of the ISP: relative size, peak-hour period, upstream-to-downstream ratio, etc. For example,  $\gamma = 0.5$  corresponds to the case where the peering traffic amounts to  $1/(1+\gamma) = 2/3$  of all the traffic of the ISP (as in Japan [14] and other localized markets), while  $\gamma = 4$  corresponds to the case where  $1/(1+\gamma) = 20\%$  of the total ISP traffic is exchanged at the IXP, and the remaining 80% is transferred through transit (this situation is common in small markets [3]). The empirical evidence of few European ISPs discussed in the Appendix suggests that  $\gamma$  belongs to  $[1.5, 2]$  for medium-size European countries with one dominant IXP.

3) *Pricing Model*: In the following evaluation, we use the pricing model (described in Section II) with prices given in Table I and upstream/downstream traffic billed with either sum or max model. In Section V-B, we describe the results of a comparative study of both sum and max models. In Sections V-C–V-E, we focus on the sum pricing model (the more conservative one in terms of cost reduction) for the analysis of cost sharing, coalition size, and geo-diversity.

## B. Aggregate Savings

In this section, we evaluate the aggregate potential savings of the IP transit costs for the coalitions consisting of *all* members within each IXP listed in Table II. Following the discussion in Section V-A.2, we approximate the IP transit traffic patterns by the traffic exchanged at these IXPs multiplied by constant  $\gamma \in [0.5, 4]$ ; this constant represents the ratio between the transit and peering traffic volumes.

We stress again that the purpose of this evaluation is to shed some light on the potential savings of CIPT rather than computing accurate bounds of the savings. Such exact saving estimates strongly depend on various factors and should be calculated on a case-by-case basis.

For each of the six studied IXPs, Fig. 4 reports the expected savings on the IP transit bill, both relative and absolute, in both the sum and max models. We see that the relative savings are in the range of 5%–70% depending on the relative size of the IXPs and several other factors. These relative savings are strongly impacted by the size distribution of the involved ISPs. Namely, for those IXPs that have several large ISPs that dominate the traffic (and the costs), the relative savings of CIPT are low because these large ISPs already receive the lowest price per *Mbps*. To illustrate that this is indeed the case, we define the *skewness* factor as the fraction of the traffic generated by the players with the peak traffic greater than 10 *Gbps*. Table II shows that the expected relative savings are considerably higher for the IXPs with a low *skewness* of under 0.3 (SIX, IIX, and InterLAN).

Remember that the savings of CIPT come from two properties of the IP transit model: price subadditivity and 95th-percentile billing. To quantify the effects that these two properties have on the CIPT savings, we identified what the relative savings would be without the subadditivity of the prices, i.e., if the price per *Mbps* would be constant independent of the usage level. Such savings would come exclusively from the reduction in the 95th-percentile; the rest of the savings would hence correspond to the subadditivity effect. Table II presents these results in columns *95th-pct effect* and *subadditive effect*, respectively. From this table, we can conclude that both properties (price subadditivity and 95th-percentile billing) influence the total savings.

The decreasing trend of relative savings can be observed in both sum and max pricing models. The decrease happens because the players with large volumes have smaller opportunities for large relative savings by CIPT (as they already experience a low price per *Mbps*). Nevertheless, the relative savings are bounded from below by the quantity of the *95th-pct effect* reported in Table II for both sum and max pricing models. Fig. 10 in the Appendix replots the above findings to directly demonstrate that the sum model is indeed more conservative than the max model with respect to the attained CIPT gains.

We conclude this analysis with an observation that the six (medium-size European) countries hosting these IXPs have such traffic locality that around 40% of the traffic stays inside the country and is exchanged by peering (mainly through the dominant IXP), while the remaining 60% of the traffic uses IP transit (see the Appendix). This corresponds to value  $\gamma$  of 1.5. Using this value of  $\gamma$ , we conclude that the expected relative

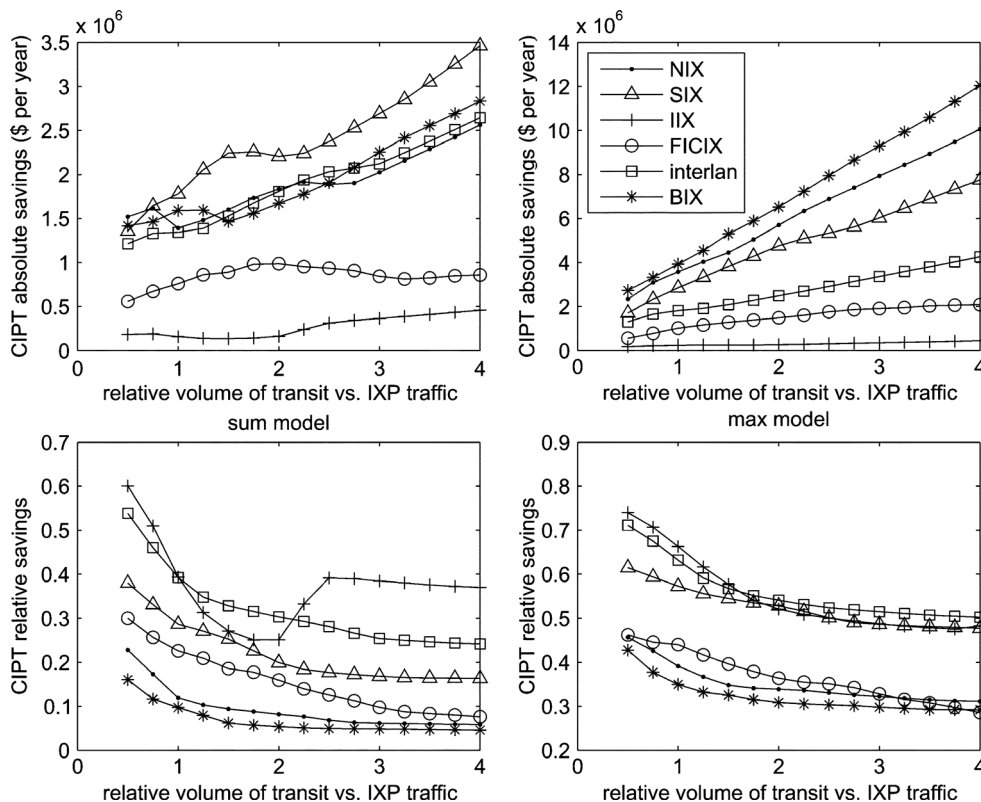


Fig. 4. Absolute and relative savings as a function of the ratio between the transit and IXP traffic volumes.

savings in IP transit costs for the IXP-wide CIPT coalitions are in the range of 8%–35% (in the sum model) and 32%–56% (in the max model).

While we rely on the pricing function of a middle-size transit provider, the pricing function of a larger provider can yield further quantity discounts: If a transit provider attracts large customers, the provider can offer discounts on larger volumes than alternative smaller transit providers, i.e., there are greater economies of scale with a large transit provider than with a smaller one.

On the other hand, regardless of how large the transit provider is, the additional discounts are finite. Therefore, starting from some huge traffic volume, CIPT cannot benefit from further discounts. At such traffic volumes, CIPT gains arise due to the 95th-percentile effect rather than the subadditive effect.

### C. Coalition Size

In Section V-B, we analyzed the potential savings of coalitions that include *all* members of the corresponding IXPs. While such coalitions offer significant savings in terms of IP transit costs, coordination of such large coalitions may be cumbersome. In this section, we show that much smaller coalitions can offer savings comparable to those of the large coalitions. We take the Slovak IXP (SIX) with  $N = 52$  members, and for each  $k \in \{1, 2, \dots, N\}$ , we analyze the per-player savings from participating in the coalition of  $k$  random members of SIX. The pricing model is sum, and  $\gamma$  is set to 1.5. The results for other IXPs, max pricing model, and other choices of  $\gamma$  are qualitatively similar, hence we omit them for brevity.

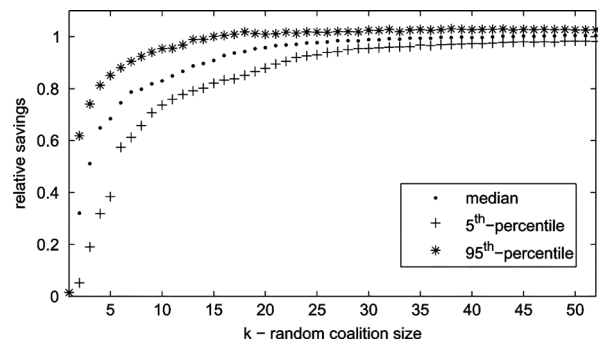


Fig. 5. Relative (as fraction of the savings obtained in the grand coalition) per-player savings for smaller coalitions.

In Fig. 5, we report the median, 5th-percentile, and 95th-percentile savings, relative to the savings obtainable from the grand coalition of all  $N = 52$  members. Since analyzing the statistics across all  $2^{52}$  subsets is infeasible, we report the results obtained by sampling: For each member  $i$  and each coalition size  $k$ , we pick random 100 subsets of size  $k$  that contain member  $i$ . From Fig. 5, we can observe the law of diminishing returns: Relatively small coalitions provide savings very close to the savings of the large coalitions, and by adding more members to the coalition, the incremental savings are decreasing. In particular, even with as few as  $k = 3$  members, one can expect savings that are half as large as the savings obtainable by the coalition of all  $N = 52$  members. With  $k \geq 10$  members, the median CIPT savings are greater than 80% of the savings obtainable by the grand coalition.

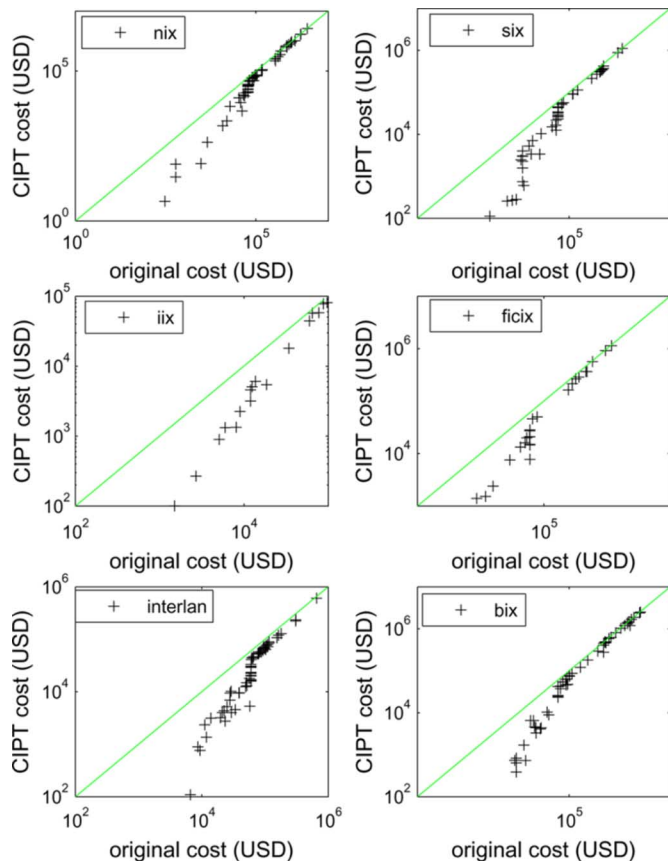


Fig. 6. Original annual costs versus CIPT costs (Shapley value) across all the ISPs from the six IXPs.

Note that the savings grow as the coalitions become larger. This is the consequence of the basic property of the CIPT cooperative game: The cost function is subadditive, as seen in (1). In other words, by adding a member, the coalition is better off. Also, note that for some ISPs, participating in some smaller coalitions may be more beneficial than participating in the grand coalition (the relative savings exceed 1).

We stress that the results of this section are for random coalitions. By carefully cherry-picking the most appropriate partners, one can obtain even higher savings, as the 95th-percentile of the savings in Fig. 5 suggests. However, such optimization is out of scope for the present paper.

#### D. Per-Partner Savings

In this section, we look at the per-member savings for each of the involved ISPs when it participates in the IXP-wide CIPT. Following the reasoning described in Section V-A.2, the  $\gamma$  factor used for scaling of the transit traffic is set to 1.5, and the pricing model is the more conservative sum model. As we elaborate in Section IV, each member of the coalition is assigned a cost equal to its Shapley value. The CIPT costs (across all ISPs) are depicted in Fig. 6 against the original IP transit annual costs. Fig. 7 shows the absolute annual savings (the difference between the original IP transit costs and CIPT costs) for all ISPs in these six IXPs.

We can observe two trends in Figs. 6 and 7. First, the absolute savings typically grow with the size of the ISP. This is a

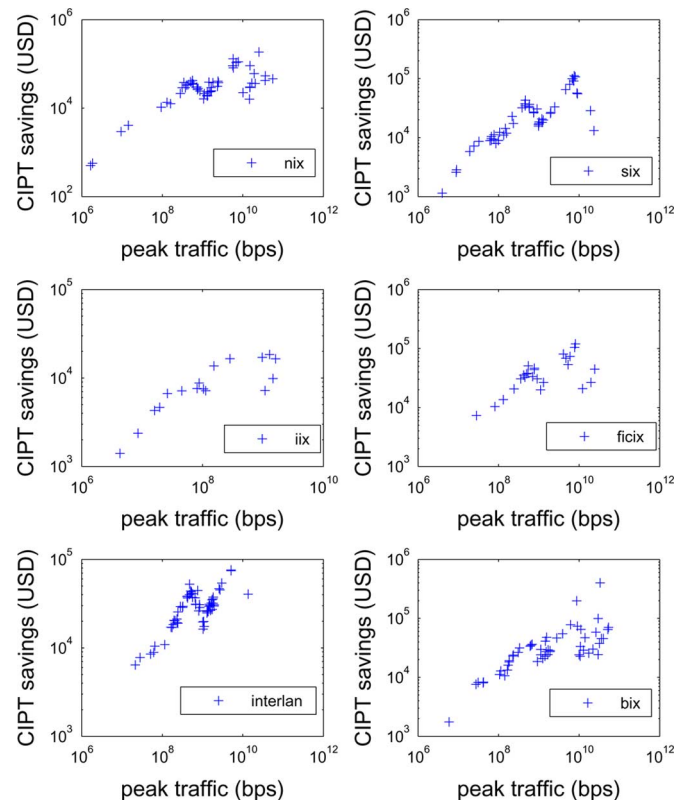


Fig. 7. Absolute annual savings for all the ISPs from the six IXPs.

consequence of the fact that having a large ISP in a coalition typically implies lower per-Mbps costs, which in turn increases the contribution of the ISP to the coalition, as reflected by the computation of the Shapley value in (2). Therefore, a large ISP can benefit from joining a coalition because the gains are computed as a total and then redistributed using the Shapley value; even if such a large ISP does not obtain a further price discount, other ISPs do generate gains of which the large ISP benefits.

In contrast to this increasing trend of the absolute savings, there is another interesting property of the CIPT cost allocation. Namely, the relative savings of CIPT (the ratio of the absolute savings of CIPT to the original IP transit costs) typically see a decreasing trend as a function of the ISP size. This feature (decreasing trend of the relative savings) is strongly connected with the nature of the Shapley value as a cost allocation strategy, but arises also because peak time of the aggregate traffic is predominantly determined by the large ISPs. This means that ISPs joining already larger coalitions (those that reached a close-to-minimum price per Mbps) bring lower relative benefits to the coalitions, consequently implying low relative gains for these ISPs. While the Shapley value computes the expected contribution of an ISP regardless of when it joins the coalition, absolute gains growth exhibits a decreasing trend. Consequently, relative gains decrease as the ISP size grows.

#### E. Cooperation Between Remote Subjects

So far, our analysis was concerned with the ISPs operating in the same geographic area, and consequently having close peak hours. In such scenarios, the savings are mainly impacted by the price subadditivity rather than the burstable billing. In



this section, we investigate potential savings of collaboration between geographically distant players. Because the remote collaboration involves IP transport costs, it is possible only for large players. Only then, the long-distance transport becomes cheap enough to make the CIPT economically viable [33]. Such long-distance transport to major (cheap) Internet hubs is not an uncommon method for ISP cost optimization. For example, each of the four largest IXPs—DE-CIX (German Commercial Internet Exchange), AMS-IX (Amsterdam Internet Exchange), LINX (London Internet Exchange), and NYIIX (New York International Internet Exchange)—host ISPs from more than 40 different countries.

Additionally, cooperation between very remote subjects (say, more than six time zones), may strongly impact the performance in terms of increased propagation delays. Some delay-sensitive applications (voice, gaming, etc.) may find such increase in delay unacceptable. Therefore, CIPT between very remote subjects is reasonable only for the traffic that is not delay-sensitive (content, p2p, etc.), which indeed represents the majority of the Internet traffic [42], [45], [54].

While identifying and separating delay-tolerant traffic from non-delay-tolerant traffic is not trivial, the respective technical challenges have already been addressed [45], [54]. Even though traffic separation might be viewed as a network-neutrality violation, it might be also regarded as acceptable for performance reasons [20]. Since our goal is to show the economic attractiveness of CIPT, we focus on potential gains from CIPT between remote subjects, rather than on its technical implementation or net-neutrality aspects.

To analyze the potential savings in such a setup, we look at the potential savings of collaborations with *two* partners. Once *all* the partners are large enough to receive the minimum per-Mbps price, the coalitions with more than two partners are not bringing large marginal benefits in terms of price reduction. Thus, we here focus on 2-partner coalitions. To assess the potential savings in such cases, we take all  $M = 93$  ISPs from our six IXPs with the peak traffic greater than 1 Gbps and shift each of them for a (uniformly) random number of time zones. For each of the  $M(M-1)/2$  pairs, we evaluate the relative savings of the coalition,  $1 - \text{cost}(\text{CIPT}(i, j)) / (\text{cost}(i) + \text{cost}(j))$ , and plot them against the time difference in Fig. 8. One can observe the following trend: The farther away the two partners are, the greater the opportunity is for the CIPT savings. In Fig. 8, we also depict the bound

$$g(\psi) = \frac{1 - \left| \cos \frac{\psi}{2} \right|}{2} \quad (4)$$

where  $\psi = \frac{\text{time\_difference}}{24} 2\pi$  is the scaled time difference. We prove the upper bound on the relative savings in a simple model where the demand curves are modeled as sin-waves (see below). One can observe that the relative reduction in the 95th-percentile for a coalition of two partners is in the range of  $[0, 0.5]$ , in line with the model predictions. However, the expected savings appear to be larger as the time difference grows, and peak when two ISPs are 12 time zones apart. To explain and quantify this property, we employ a simple trigonometric model where the demand pattern of the ISP is modeled as a sin-wave function.

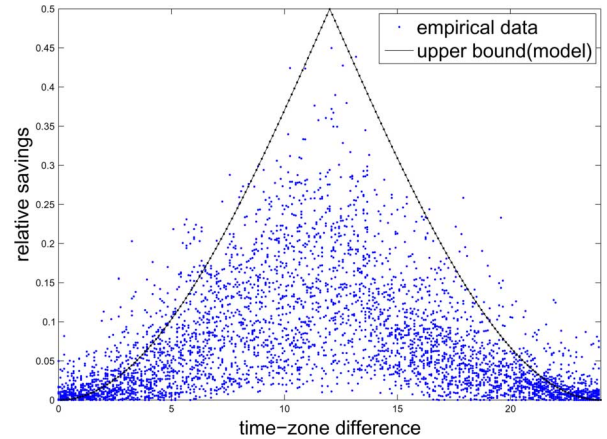


Fig. 8. Relative savings between large remote subjects coming from the 95th-percentile subadditivity.

The following proposition characterizes the expected reduction in the peak traffic from CIPT collaboration between two partners with noncoinciding peak hours.

*Proposition 1:* Let two players have demand given by

$$D_i(t) = A_i \cos\left(2\pi \frac{t - M_i}{24}\right) + B_i, \quad t \in [0, 24) \text{ hours}$$

where  $B_i$  is the mean traffic intensity,  $A_i + B_i$  is the peak traffic intensity, and  $M_i$  is the peak hour of partner  $i$ . By creating a CIPT coalition between these two partners, the relative reduction in the peak is equal to

$$G_{12} = 1 - \frac{B_1 + B_2 + \sqrt{A_1^2 + A_2^2 - 2 \cos \psi A_1 A_2}}{B_1 + B_2 + A_1 + A_2} \leq g(\psi)$$

for  $\psi = \frac{M_1 - M_2}{24} 2\pi$ , the scaled time-zone difference, and  $g(\psi)$  defined in (4).

## VI. IMPLEMENTATION AND DEPLOYMENT ISSUES

Section V-D presented compelling evidence that CIPT with Shapley-value sharing of transit costs offers significant benefits to the CIPT partners. While the economic incentives are crucial for CIPT being viable, the viability is a topic with multiple dimensions. Without pretending to be comprehensive, this section discusses other aspects of CIPT such as its organizational embodiment, physical infrastructure, performance, traffic confidentiality, and interdomain routing.

*Organizational Embodiment:* CIPT is an innovative mechanism for reducing transit costs. Among other cost-reduction mechanisms, peering is similar to CIPT in its cooperative nature and commonly organized as a nonprofit IXP. In our vision for CIPT as an organization, a typical arrangement is also a nonprofit organization. The nonprofit status of a CIPT promotes a valuable marketplace image of its neutrality and fair treatment for all its partners. In such an organization, partnership fees are used only to recover the technical and management overhead costs of operating the CIPT and expected to be insignificant in comparison to the transit cost reductions provided by the CIPT. In a future study, we plan to quantify the technical and economic overhead. While the nonprofit arrangement looks the most suitable, deviations are quite possible and even likely;

as with some existing IXPs, some CIPTs might operate as government or commercial organizations. Finally, a single ISP may choose to participate in multiple CIPTs in order to increase the provider diversity.

*Physical Infrastructure:* The physical implementation is another issue where CIPTs can benefit from the IXP experience. For buying IP transit in bulk, a CIPT needs to concentrate traffic of multiple ISPs in one location. The physical infrastructure of any IXP already supports such concentration for peering purposes. Moreover, some IXPs diversify their service portfolio by offering access to transit providers. For example, Vancouver Transit Exchange is an IXP that also hosts transit providers and thereby enables an ISP to satisfy its peering and transit needs at the same location [39]. A CIPT can be implemented as a further diversification of the IXP service portfolio. By leveraging the physical infrastructure of an existing IXP, the CIPT can keep its operational costs low.

*Performance:* A CIPT and its transit provider sign a contract for IP transit. The contract is expected to be of the same type as existing contracts between an individual ISP and its transit provider. In particular, the contract includes a Service Level Agreement (SLA) stating the maximum outage duration, packet delay, jitter, and loss rate for the CIPT traffic. The SLA also specifies financial compensations by the provider if the latter fails to provide the CIPT with the agreed performance. In reality, SLA violations are likely to be rare. Whereas the performance levels of traditional interprovider SLAs are very similar, having a single SLA for the multiple-partner CIPT is not problematic. Also, the typical SLA metrics of packet delay, jitter, and loss rate are such that the traffic of individual CIPT partners can inherit the performance levels of the CIPT aggregate traffic without any special technical support. Furthermore, the CIPT and its individual partner can sign a separate bilateral agreement on performance issues.

*Traffic Confidentiality:* While it is feasible to formalize traffic metering and billing for a CIPT by means of bilateral agreements between the CIPT and each of its individual partners, the bill of a partner depends on the traffic of the other partners. Some academic ISPs—such as the aforementioned HEANET, SANET, GRNET, and CESNET—reveal their transit and peering traffic. However, a typical commercial ISP tends to be more secretive and does not disclose its traffic patterns. To alleviate the privacy concerns, a CIPT can keep the traffic profiles of its partners confidential and incorporate an internal audit system for verifying the correctness of traffic metering and billing for each partner.

*Interdomain Routing:* With Border Gateway Protocol (BGP) being a *de facto* standard protocol for routing between autonomous systems (ASs), we see no technical complications with CIPTs from the interdomain routing perspective. A CIPT can acquire a separate AS number for inclusion into its BGP path announcements. Alternatively, as in the case of some IXPs, the partners of a CIPT can agree to use the individual AS number of one (typically, prominent) partner in all BGP announcements by the CIPT.

*Multihoming and Traffic Engineering:* Both are feasible with CIPT. A CIPT partner can buy transit outside the CIPT as well. Also, a CIPT can buy transit from multiple providers. While

multihoming might increase costs, CIPT can reduce these costs due to price subadditivity and burstable billing.

*Social Impact:* The overall social impact of CIPTs appears positive. In particular, CIPTs are beneficial for narrowing the digital divide between the developed countries and poorer world that lies on the Internet edges and does not own a transit infrastructure for reaching the Internet core. In places like Africa, IP transit (and IP transport) is more expensive, but the ability to pay for it is lower. Like with IXPs that have positively affected Africa by exchanging its traffic locally rather than through North America or Europe, CIPTs can benefit Africa and other developing regions by making the access to the Internet and its information more affordable [3], [34].

## VII. CIPT: A STRATEGIC PERSPECTIVE

In this section, we analyze potential strategic reactions to and within CIPT. While a CIPT coalition can include members with different market power, more powerful members can try to gain extra benefits by leveraging their stronger bargaining position against weaker members of the coalition. Moreover, CIPT participation depends on existing or potential transit and peering relationships. Section VII-B examines such issues related to CIPT formation and participation. Strategic CIPT issues are also relevant to ISPs that are not directly involved in CIPT relationships. Other individual customer ISPs can react by forming their own CIPT coalitions. More interestingly, both the transit provider of the CIPT members and its competitors can adjust their strategic behaviors in response to the CIPT emergence. Section VII-A studies the reactions of transit providers.

### A. Transit Providers

Whereas transit customers form a CIPT for the simple reason of reducing their costs, the reaction of transit providers to CIPT is a multifaceted issue. Somewhat counterintuitively, the transit providers can favor CIPT for a number of reasons.

One potential incentive for an interest of transit providers in CIPT lies in transit traffic elasticity [73]. By decreasing the transit costs of individual buyers, CIPT increases their future demands. While we had no access to reliable data on transit elasticity, our paper quantified the benefits of CIPT conservatively without these extra gains. Also, regardless of whether a transit provider is a monopolist, CIPT increases overall demand by turning prospective buyers into actual customers via aggregation of their individual demands. Moreover, CIPT traffic aggregation can enable the transit provider to bypass resellers of its transit service and serve small customers directly through the CIPT. Finally, if the transit provider is not a monopolist, it can adopt CIPT contracts to attract new customers from its competitors.

Traffic aggregation can allow small customers to pool their traffic together and become attractive customers for transit providers. More generally, direct provisioning of transit to small customers is sometimes unattractive for big ISPs. Instead, mid-size networks resell transit of big ISPs to small customers. By aggregating traffic of multiple small members, a CIPT can reach an acceptable size for direct transit sales by a big ISP. Such outcome can be mutually beneficial for

both the CIPT and transit provider. While our paper already elaborated on the benefits for the CIPT members, the transit provider benefits as well by selling the same traffic at higher per-*Mbps* prices than through the intermediary. Even though the bypassed intermediary does not find the CIPT beneficial, the reseller does not have effective means or clear grounds to oppose the direct relationship between the CIPT and big ISP.

Additionally, in situations where the transit market is competitive, a transit provider can try adopting CIPT to increase its revenues at the expense of its competitors which, in their turn, can try doing the same. The competition for CIPT contracts drives per-*Mbps* CIPT prices down. In Bertrand competition model for homogeneous goods, such competitions converge to the so-called Bertrand paradox where the competitors offer prices that match their costs, i.e., yield no profit [72]. In practice, while transit providers are sufficiently heterogeneous (e.g., with respect to geographic coverage, service quality, and cost structure) to avoid the extreme no-profit outcome, their actual prices are still likely to be attractive for CIPT coalitions.

In theory, transit providers can also benefit from CIPTs due to a variety of other economic factors that include transaction efficiency, traffic uncertainty, customer heterogeneity, and production postponement [4]. In the current context of IP transit, these factors do not appear to be strong enablers of CIPT. Thus, we view the traffic aggregation and interprovider competition as the two main reasons for the CIPT feasibility from the transit-provider perspective.

### B. Strategic Issues Within the CIPT Coalition

Strategic issues exist within a CIPT coalition as well. One specific issue is CIPT formation, i.e., which ISPs join the coalition. Another interesting issue is CIPT cost sharing, i.e., whether and how the CIPT members can leverage the Shapley-value cost sharing mechanism for their individual advantages.

Peering and transit relationships of CIPT members, as well as their position in the transit hierarchy, are relevant to CIPT formation. Both peering and CIPT are mechanisms for transit-cost reductions. By reducing transit costs, CIPT can decrease the value of peering. Due to this effect, ISPs with established peering relationships can be reluctant to join CIPTs. For the same reason, CIPT members can be reluctant to enter peering relationships. This tension between CIPT and peering can increase demand for traditional transit and thereby serve as an additional incentive for transit providers to support CIPT.

As we discuss in Section VII-A, CIPT makes a negative impact on bypassed transit resellers. To compensate for the diminished revenues, a bypassed reseller can itself join a CIPT in order to minimize the losses.

So far, our analysis considered static situations only. CIPT dynamics broaden the scope of potential strategic behaviors. For example, if an ISP joins a CIPT coalition with a certain traffic contribution and later communicates at a different rate, the ISP traffic change affects the gains achieved by other CIPT members. To deal with such future traffic uncertainties, CIPT coalitions can adopt a mechanism that requires each member to commit to an expected traffic level for some time period.

## VIII. RELATED WORK

In presenting and evaluating CIPT, we already mentioned the essential background information. This section takes a broader look at related work.

Our study of CIPT starts with the observations that inter-domain traffic grows and that IP transit costs are high. The traffic growth is a long-term trend [14], [44], even though the main application fueling the growth has been changing from Web browsing [29] to P2P file sharing [71] to video streaming [61]. The recent investigation of 110 geographically diverse ISPs estimates the annual rate of the interdomain traffic growth at 44.5% [44]. Other reports cite even higher annual growth rates in the range of 50%–60% [17], [55]. Whereas the IP transit is a competitive business, the transit prices per *Mbps* decline [22] but at lower rates of about 25%–30% per year [33]. In spite of the falling IP transit prices, ISP business analysts agree that the overall IP transit costs remain high or even increase [10], [32], [43].

The existing approaches for reducing the transit costs include ISP peering, IP multicast, CDNs, P2P localization, and traffic smoothing. Peering [6], [23], [50] enables two ISPs to exchange their traffic directly, rather than through a transit provider at a higher cost. To disseminate data to multiple receivers, IP multicast [7], [11], [21], [35], [36] duplicates packets in IP routers and thereby reduces transit traffic. While IP multicast requires router support from transit providers, CDNs [59] and P2P systems duplicate data on the application level. Whereas a single company controls a CDN, a P2P system consists of independent hosts, and P2P localization [15] strives to reduce transit traffic without undermining the system performance. Even if the transit traffic preserves its volume but is redistributed within the billing period to peak at a lower value, the transit costs decrease due to the burstable billing [27]. An ISP can do such traffic smoothing [42] with rate limiting [54] or in-network storage for delay-tolerant traffic [45]. Unlike the above approaches that modify the transit traffic, CIPT reduces the transit costs without altering it.

CIPT reduces transit costs by means of traffic aggregation. In the early 1990s, TLG [48] used transit aggregation to reduce Internet access prices in northern California. Small customers pooled their traffic together to obtain cheaper rates from UUNET. IXPs also act as transit aggregators. For example, government-promoted Bahrain IXP [9] lowers transit costs through national transit traffic aggregation [63]. IXPs in other developing countries in Africa and Asia play a similar role [3], [34]. Even though transit aggregation is a frequent practice, CIPT is substantially different from prior schemes because of its cooperative essence. TLG was never a cooperative of transit buyers: From its beginning, TLG acted as a commercial transit reseller and treated individual buyers as customers, not as partners [60]. Similarly, the transit-aggregating IXPs do not rely on cooperation of individual transit buyers.

We view CIPT as a coalition and use the Shapley value [65] for sharing CIPT costs. Shair [40] is a cooperative system for a different application of sharing mobile phone minutes that enables phone users to share the committed but unused minutes. Cooperative approaches have also been studied for cost sharing in IP multicast [5], [31] and interdomain routing [53], [66], [67].

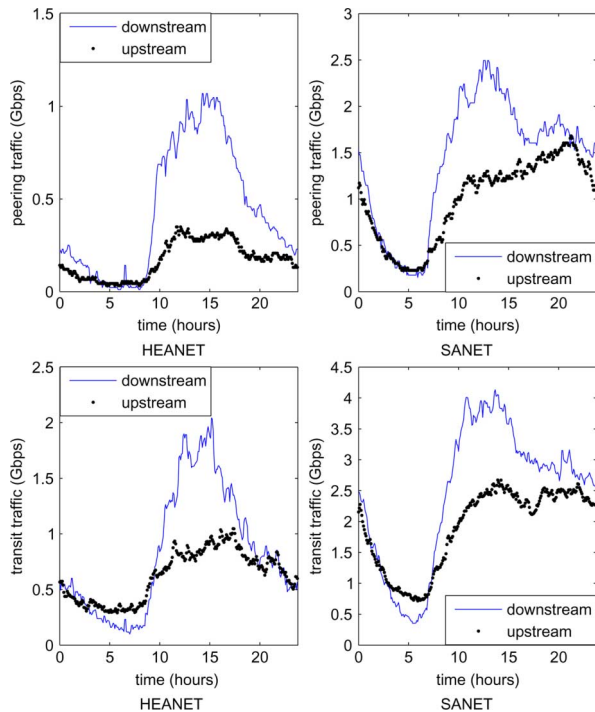


Fig. 9. Transit and peering traffic in two national ISPs: HEANET and SANET.

The game-theoretic analyses of the Shapley-value mechanism [5], [31], [57] highlight its group-strategyproofness and other salient properties but identify its high computational complexity. Despite the computational complexity, various proposals of traffic billing between ISPs [51], [52], incentives in P2P systems [56], and charging individual users by access ISPs [70] rely on the Shapley value. Unlike the above applications of IP multicasting, ISP billing, P2P incentives, and individual user charging that involve a large number of parties, CIPTs are likely to be small in size. For CIPTs with few dozens of partners, the exact computation of the Shapley value is computationally feasible. Our evaluation of CIPTs uses the Monte Carlo method to estimate the Shapley value accurately [47].

CIPT can benefit from multihoming [2], [25] by connecting to multiple transit providers. While the connection reliability is a traditional rationale for multihoming, the latter also offers interesting tradeoffs between performance and costs.

As a new element of the Internet ecosystem, CIPT diversifies the means for the economic tussle between Internet stakeholders [18], [19]. Network neutrality refers to potential restrictions on ISP traffic management [20]. Similarly to peering or content caching [22], CIPT reduces transit costs without violating the network neutrality.

## IX. CONCLUSION

In spite of the steady decline of IP transit prices, the IP transit costs remain high due to the traffic growth. Over the previous decades a number of solutions have been suggested to reduce these IP transit costs, including settlement-free or paid peering, IP multicast, CDNs, and P2P localization.

In this paper, we propose an alternative cost-reduction technique of Cooperative IP Transit (CIPT) that, in contrast to the

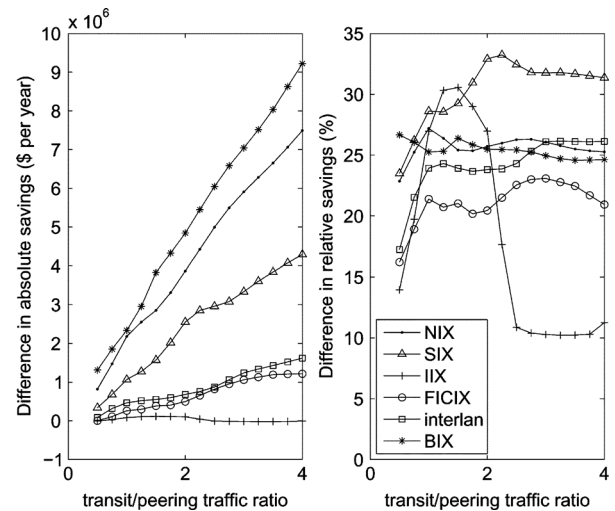


Fig. 10. Differences in CIPT savings with the max versus sum models.

existing solutions, does not alter the traffic. Namely, CIPT utilizes *tuangou*, or group buying, for IP transit. The savings in CIPT come from two distinct yet ubiquitous properties of the IP transit pricing model: price subadditivity and burstable billing. Our data-driven analysis suggests that significant savings can be expected from using CIPT. We are confident that the potential savings of CIPT, combined with its simplicity, will encourage many Internet entities to engage in CIPT partnerships.

We conclude the paper with several open problems that are the focus of our current investigation.

*Open Problem 1:* How do changes in CIPT, both in terms of the coalition structure and volume/temporal effects, affect its dynamic?

*Open Problem 2:* Can we quantify the factors (size, social, market, geography) that influence the CIPT coalition formation process?

*Open Problem 3:* Shapley value is an implicit metric: It depends not only on the player's behavior, but also on the behavior of the other partners in the CIPT. Can we derive more suitable metrics that would approximate the Shapley value closely while being explicit and simple to calculate?

## APPENDIX

### RELATION OF TRANSIT TO PEERING TRAFFIC

Here, we discuss the relationship of the transit and peering traffic in two academic ISPs that publish their network load information: HEANET and SANET. In Fig. 9, we depict the peering and transit traffic for both ISPs on Thursday, January 13, 2011. One can observe that the peering and transit traffic profiles are rather similar. To quantify the similarity of the demand patterns, we use the *cosine*-similarity between the corresponding demand time series:  $X = (x_1, \dots, x_T)$  and  $Y = (y_1, \dots, y_T)$

$$\text{sim}(X, Y) = \frac{\sum_{i=1}^T X_i Y_i}{\sqrt{\sum_{i=1}^T X_i^2} \sqrt{\sum_{i=1}^T Y_i^2}}.$$

The value of  $\text{sim}(X, Y)$  is equal to the cosine of the angle between the vectors  $X$  and  $Y$  in the  $T$ -dimensional Euclidian

TABLE III

*cosine*-SIMILARITY BETWEEN THE TRANSIT (T) AND PEERING (P) TIME SERIES (BOTH DOWNSTREAM AND UPSTREAM DIRECTIONS)

ISP	$\text{sim}(T_{up}, P_{up})$	$\text{sim}(T_{down}, P_{down})$
HEANET	0.988	0.965
SANET	0.996	0.991

space. Thus,  $\text{sim}(X, Y) = 1$  if  $X = \alpha Y$  for a scalar  $\alpha$ ; otherwise  $\text{sim}(X, Y) < 1$ . Table III reports the values of *cosine*-similarity for the upstream and downstream time series for the both ISPs.

*Comment 2:* We do not report the statistics from the other two ISPs mentioned in Section V-A.2, CESNET [13] and GRNET [37], because their visual *rrdtool* images were very nonstandard and our OCR tool could not extract numeric data from them. Nevertheless, simple visual checking confirms that the transit-peering relationships in these two networks are very similar to those observed in HEANET and SANET.

## REFERENCES

- [1] B. Ager, N. Chatzis, A. Feldmann, N. Sarrar, S. Uhlig, and W. Willinger, "Anatomy of a large European IXP," in *Proc. ACM SIGCOMM*, 2012, pp. 163–174.
- [2] A. Akella, B. Maggs, S. Seshan, A. Shaikh, and R. Sitaraman, "A measurement-based analysis of multihoming," in *Proc. ACM SIGCOMM*, 2003, pp. 353–364.
- [3] C. Amega-Selorm, M. Mureithi, D. Pater, and R. Southwood, "Impact of IXPs—A review of the experiences of Ghana, Kenya, and South Africa" Open Society Institute, 2009.
- [4] K. S. Anand and R. Aron, "Group buying on the Web: A comparison of price-discovery mechanisms," *Manage. Sci.*, vol. 49, no. 11, pp. 1546–1562, 2003.
- [5] A. Archer, J. Feigenbaum, A. Krishnamurthy, R. Sami, and S. Shenker, "Approximation and collusion in multicast cost sharing," *Games Econ. Behav.*, vol. 47, no. 1, pp. 36–71, 2004.
- [6] B. Augustin, B. Krishnamurthy, and W. Willinger, "IXPs: Mapped?," in *Proc. ACM SIGCOMM IMC*, 2009, pp. 336–349.
- [7] T. Ballardie, P. Francis, and J. Crowcroft, "Core based trees (CBT)," in *Proc. ACM SIGCOMM*, 1993, pp. 85–95.
- [8] G. Biczok and T. A. Trinh, "A user-influenced pricing mechanism for Internet access," in *Proc. ICQT*, 2009, pp. 48–60.
- [9] "Bahrain Internet Exchange," [Online]. Available: <http://www.bix.bh>
- [10] V. Bonneau, "Internet traffic and economics," presented at the Digi-World Summit 2010.
- [11] J. W. Byers, M. Luby, and M. Mitzenmacher, "A digital fountain approach to asynchronous reliable multicast," *IEEE J. Sel. Areas. Commun.*, vol. 20, no. 8, pp. 1528–1540, Oct. 2002.
- [12] I. Castro and S. Gorinsky, "T4P: Hybrid interconnection for cost reduction," in *Proc. IEEE NetEcon*, 2012, pp. 178–183.
- [13] CESNET, "Traffic stats," [Online]. Available: <http://www.ces.net/netreport/>
- [14] K. Cho, K. Fukuda, H. Esaki, and A. Kato, "The impact and implications of the growth in residential user-to-user traffic," in *Proc. ACM SIGCOMM*, 2006, pp. 207–218.
- [15] D. R. Choffnes and F. E. Bustamante, "Taming the torrent: A practical approach to reducing cross-ISP traffic in peer-to-peer systems," in *Proc. ACM SIGCOMM*, 2008, pp. 363–374.
- [16] R. Stanojevic, "CIPT dataset," 2011 [Online]. Available: [http://fourier.networks.imdea.org/people/~rade\\_stanojevic/CIPTdata/](http://fourier.networks.imdea.org/people/~rade_stanojevic/CIPTdata/)
- [17] Cisco Systems, San Jose, CA, USA, "Cisco visual networking index: Forecast and methodology," Cisco White Paper, 2008.
- [18] D. Clark, "Combining sender and receiver payments in the Internet," in *Proc. TRPC*, 1996, pp. 95–112.
- [19] D. Clark, J. Wroclawski, K. R. Sollins, and R. Braden, "Tussle in cyberspace: Defining tomorrow's Internet," in *Proc. ACM SIGCOMM*, 2002, pp. 347–356.
- [20] J. Crowcroft, "Net neutrality: The technical side of the debate: A white paper," *Comput. Commun. Rev.*, vol. 37, no. 1, pp. 49–56, 2007.
- [21] S. Deering, "Multicast routing in a datagram Internetwork," Ph.D. dissertation, Stanford University, Stanford, CA, USA, 1991.
- [22] A. Dhamdhere and C. Dovrolis, "Can ISPs be profitable without violating network neutrality?," in *Proc. ACM NetEcon*, 2008, pp. 13–18.
- [23] A. Dhamdhere and C. Dovrolis, "The Internet is flat: Modeling the transition from a hierarchy to a peering mesh," in *Proc. ACM CoNEXT*, 2010, Art. no. 21.
- [24] A. Dhamdhere, C. Dovrolis, and P. Francois, "A value-based framework for Internet peering agreements," in *Proc. ITC*, 2010, pp. 1–8.
- [25] A. Dhamdhere and C. Dovrolis, "Twelve years in the evolution of the Internet ecosystem," *IEEE/ACM Trans. Netw.*, vol. 19, no. 5, pp. 1420–1433, Oct. 2011.
- [26] A. Dhamdhere, C. Dovrolis, and K. Claffy, "Measuring the evolution of Internet peering agreements," in *Proc. IFIP Netw.*, 2012, pp. 136–148.
- [27] X. Dimitropoulos, P. Hurley, A. Kind, and M. Stoecklin, "On the 95-percentile billing method," in *Proc. PAM*, 2009, pp. 207–216.
- [28] M. Dischinger, M. Marcon, S. Guha, K. P. Gummadi, R. Mahajan, and S. Saroiu, "Glasnost: Enabling end users to detect traffic differentiation," in *Proc. NSDI*, 2010, p. 27.
- [29] F. Douglass, A. Feldmann, B. Krishnamurthy, and J. Mogul, "Rate of change and other metrics: A live study of the World Wide Web," in *Proc. USITS*, 1997, p. 14.
- [30] "European Internet Exchange Association," [Online]. Available: <http://www.euro-ix.net>
- [31] J. Feigenbaum, C. Papadimitriou, and S. Shenker, "Sharing the cost of multicast transmissions," *J. Comput. Syst. Sci.*, vol. 63, no. 1, pp. 21–41, 2001.
- [32] B. Fletcher, "Renesys official blog," 2010 [Online]. Available: <http://www.renesys.com/blog/2010/10/internet-transit-sales-2005-10.shtml>
- [33] Telegeography, Washington, DC, USA, "Global Internet geography," Tech. Rep., 2010 [Online]. Available: <http://www.telegeography.com/product-info/gig/download/telegeography-global-internet.pdf>
- [34] Global Internet Policy Initiative, "Internet exchange points. Their importance to development of the internet and strategies for their deployment, the African example," 2002 [Online]. Available: [http://intgovforum.org/Substantive\\_1st\\_IGF/IXP%20Paper.pdf](http://intgovforum.org/Substantive_1st_IGF/IXP%20Paper.pdf)
- [35] S. Gorinsky, S. Jain, H. Vin, and Y. Zhang, "Design of multicast protocols robust against inflated subscription," *IEEE/ACM Trans. Netw.*, vol. 14, no. 2, pp. 249–262, Apr. 2006.
- [36] S. Gorinsky, S. Jain, and H. Vin, "Multicast congestion control with distrustful receivers," in *Proc. Netw. Group Commun.*, 2002, pp. 19–26.
- [37] GRNET, "Traffic stats," [Online]. Available: <http://mon.grnet.gr/rg/>
- [38] HEANET, "Traffic stats," [Online]. Available: <http://www.heanet/>
- [39] M. Hrybyk, "The transit exchange—A new model for open, competitive network services," in *Proc. PTC*, 2007, pp. 1401–1417.
- [40] P. Hui, R. Mortier, K. Xu, J. Crowcroft, and V. O. K. Li, "Sharing airtime with Shair avoids wasting time and money," in *Proc. HotMobile*, 2009, Art. no. 6.
- [41] Information Sciences Institute, University of Southern California, Los Angeles, CA, USA, "Internet protocol DARPA internet program protocol specification," RFC 791, 1981.
- [42] P. Kanuparth and C. Dovrolis, "ShaperProbe: End-to-end detection of ISP traffic shaping using active methods," in *Proc. ACM SIGCOMM IMC*, 2011, pp. 473–482.
- [43] C. Weinschenk, "IP wholesale: Volume up, costs down," 2010 [Online]. Available: <http://www.itbusinessedge.com/cm/community/features/interviews/blog/ip-wholesale-volume-up-costs-down/?cs=44377&page=2>
- [44] C. Labovitz, S. Iekel-Johnson, D. McPherson, J. Oberheide, and F. Jahanian, "Internet inter-domain traffic," in *Proc. ACM SIGCOMM*, 2010, pp. 75–86.
- [45] N. Laoutaris, G. Smaragdakis, P. Rodriguez, and R. Sundaram, "Delay tolerant bulk data transfers on the Internet," in *Proc. ACM SIGMETRICS*, 2009, pp. 229–238.
- [46] C. Li, K. Sycara, and A. Scheller-Wolf, "Combinatorial coalition formation for multi-item group-buying with heterogeneous customers," *Decision Support Syst.*, vol. 49, no. 1, pp. 1–13, 2010.
- [47] D. Liben-Nowell, A. Sharp, T. Wexler, and K. Woods, "Computing Shapley value in cooperative supermodular games," Preprint, 2010.
- [48] "The Little Garden (TLG)," [Online]. Available: <http://www.wps.com/J/TLG/TLG.html>
- [49] A. Lodhi, A. Dhamdhere, and C. Dovrolis, "GENESIS: An agent based model of interdomain network formation, traffic flow and economics," in *Proc. IEEE INFOCOM*, 2012, pp. 1197–1205.
- [50] A. Lodhi, A. Dhamdhere, and C. Dovrolis, "Analysis of peering strategy adoption by transit providers in the Internet," in *Proc. IEEE NetEcon*, 2012, p. 177.

- [51] R. T. B. Ma, D. M. Chiu, J. C. S. Lui, V. Misra, and D. Rubenstein, "Internet economics: The use of Shapley value for ISP settlement," *IEEE/ACM Trans. Netw.*, vol. 18, no. 3, pp. 775–787, Jun. 2010.
- [52] R. T. B. Ma, D. M. Chiu, J. C. S. Lui, V. Misra, and D. Rubenstein, "On cooperative settlement between content, transit and eyeball Internet service providers," *IEEE/ACM Trans. Netw.*, vol. 19, no. 3, pp. 802–815, Jun. 2011.
- [53] R. Mahajan, D. Wetherall, and T. Anderson, "Negotiation-based routing between neighboring ISPs," in *Proc. NSDI*, 2005, pp. 29–42.
- [54] M. Marcon, M. Dischinger, K. P. Gummadi, and A. Vahdat, "The local and global effects of traffic shaping in the Internet," in *Proc. COMSNETS*, 2011, pp. 1–10.
- [55] University of Minnesota, Minneapolis, MN, USA, "Minnesota Internet Traffic Studies (MINTS)," 2009 [Online]. Available: <http://www.dtc.umn.edu/mints>
- [56] V. Misra, S. Ioannidis, A. Chaintreau, and L. Massoulie, "Incentivizing peer-assisted services: A fluid Shapley value approach," in *Proc. ACM SIGMETRICS*, 2010, pp. 215–226.
- [57] H. Moulin and S. Shenker, "Strategyproof sharing of submodular costs: Budget balance versus efficiency," *Econ. Theory*, vol. 18, no. 3, pp. 511–533, 2001.
- [58] T. Oetiker, "The multi router traffic grapher," 2011 [Online]. Available: <http://oss.oetiker.ch/mrtg/>
- [59] E. Nygren, R. K. Sitaraman, and J. Sun, "The Akamai network: A platform for high-performance Internet applications," *Oper. Syst. Rev.*, vol. 44, no. 3, pp. 2–19, 2010.
- [60] Personal communications with John Gilmore (TLG co-founder) and Randy Bush, 2012.
- [61] M. Podlesny and S. Gorinsky, "Leveraging the rate-delay trade-off for service differentiation in multi-provider networks," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 5, pp. 997–1008, May 2011.
- [62] Y. Rekhter and T. Li, "A border gateway protocol (BGP-4)," RFC 1771, 1995.
- [63] Renesys, Manchester, NH, USA, "Bahrain's Internet ecosystem," 2009 [Online]. Available: [http://www.tra.org.bh/en/pdf/Renesys\\_Study.pdf](http://www.tra.org.bh/en/pdf/Renesys_Study.pdf)
- [64] SANET, "Traffic stats," 2013 [Online]. Available: <http://samon.cvt.stuba.sk/>
- [65] L. S. Shapley, "A value for n-person games," *Ann. Math. Study*, vol. 28, pp. 307–317, 1953.
- [66] F. B. Shepherd and G. Wilfong, "Multilateral transport games," in *Proc. INOC*, 2005, pp. B2-378–B2-385.
- [67] G. Shrimali, A. Akella, and A. Mutapcic, "Cooperative interdomain traffic engineering using Nash bargaining and decomposition," *IEEE/ACM Trans. Netw.*, vol. 18, no. 2, pp. 341–352, Apr. 2007.
- [68] J. Sommers, P. Barford, N. Duffield, and A. Ron, "Multi-objective monitoring for SLA compliance," *IEEE/ACM Trans. Netw.*, vol. 18, no. 2, pp. 652–665, Apr. 2010.
- [69] R. Stanojevic, I. Castro, and S. Gorinsky, "CIPT: Using tuangou to reduce IP transit costs," in *Proc. ACM CoNEXT*, 2011, Art. no. 17.
- [70] R. Stanojevic, N. Laoutaris, and P. Rodriguez, "On economic heavy hitters: Shapley value analysis of the 95th-percentile pricing," in *Proc. ACM IMC*, 2010, pp. 75–80.
- [71] I. Stoica, R. Morris, D. Liben-Nowell, D. R. Karger, M. F. Kaashoek, F. Dabek, and H. Balakrishnan, "Chord: A scalable peer-to-peer lookup protocol for Internet applications," *IEEE/ACM Trans. Netw.*, vol. 11, no. 1, pp. 17–32, Feb. 2003.
- [72] J. Tirole, *The Theory of Industrial Organization*. Cambridge, MA, USA: MIT Press, 1994.
- [73] V. Valancius, C. Lumezanu, N. Feamster, R. Johari, and V. Vazirani, "How many tiers? Pricing in the Internet transit market," in *Proc. ACM SIGCOMM*, 2011, pp. 194–205.
- [74] E. Winter, "The Shapley value," in *The Handbook of Game Theory*. Amsterdam, The Netherlands: North-Holland, 2002.



**Ignacio Castro** (S'12) graduated in economics from the University Autonoma of Madrid, Madrid, Spain, in 2005, and received the M.Sc. degree in economics from the University van Amsterdam, Amsterdam, The Netherlands, in 2008, and is currently pursuing the Ph.D. degree in information and knowledge society at the Internet Interdisciplinary Institute (IN3), Open University of Catalonia, Barcelona, Spain.

He currently works as a Research Assistant with Institute IMDEA Networks, Madrid, Spain. His professional services include publicity co-chairing for COMSNETS 2014. His work appeared at ACM CoNEXT, IEEE NetEcon, and the IEEE/ACM TRANSACTIONS ON NETWORKING. His research interests focus on the economics of Internet interconnections and routing.



**Rade Stanojevic** (M'07) received the Ph.D. degree from the Hamilton Institute, NUI Maynooth, Ireland, in 2007.

He is a Researcher with Telefonica Research, Barcelona, Spain. Before his current post, he was affiliated with IMDEA Networks, Madrid, Spain, and the Hamilton Institute. His current research is centered around network economics.

Dr. Stanojevic's work on decentralized cloud control has been awarded the ACM SIGMETRICS 2008 Kenneth C. Sevcik Outstanding Student Paper Award and IEEE IWQoS 2009 Best Paper Award.



**Sergey Gorinsky** (S'97–M'05) received the Engineer degree from Moscow Institute of Electronic Technology, Zelenograd, Russia, in 1994, and the M.S. and Ph.D. degrees in computer science from the University of Texas at Austin, Austin, TX, USA, in 1999 and 2003, respectively.

From 2003 to 2009, he served on the tenure-track faculty with Washington University in St. Louis, St. Louis, MO, USA. He currently works as a tenured Research Associate Professor with Institute IMDEA Networks, Madrid, Spain. The areas of his primary

research interests are computer networking and distributed systems. His research contributions include multicast congestion control resilient to receiver misbehavior, analysis of binary adjustment algorithms, efficient fair transfer of bulk data, network service differentiation based on performance incentives, and economic perspectives on Internet interconnections and routing.