Modeling the impact of horizontal and vertical monopolies in the telecommunication market on the diversity of accessing content

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***Abstract*—We study competition between local Internet Service Providiers (ISPs) over access to content in a telecom market. We assume that the local ISPs do not have direct access to content. The content that they provide to their subscribers is assumed to originate from content providers and to transit through intermediate regional ISPs. Each local ISP is assumed to have an agreement with one given regional ISP. We consider vertical monopolies where each regional ISP has an exclusive agreement with another content provider (CP) called a "super CP". As a result, we assume that a CP favors the demand it receives from its partner regional ISP over the one it receives from other ones and likewize, a regional ISP will favor traffic from its partner CP. Thus, a local ISP seeking content from a CP will receive the content at a better quality of service or at a cheaper price if the CP is the partner of its regional ISP. Through a game theoretical analysis, we show that in spite of the non neutrality in the network, the competition between the local ISPs results in diversity in accessing content, so that at equilibrium, local ISPs do not restrict their demand to the CPs that are partners of their regional ISPs. We then further study the impact of collusions between local service providers on the access to content.**

I. Introduction

The last years have seen much public debate and legislation initiatives concerning access to the global Internet. Some of the central issues concerned the possibility of discrimination of packets by service providers according to their source or destination, the protocol used. A discrimination of a packet can occur when preferential treatment is offered to it either in terms of the quality of service it receives or in terms of the cost to transfer it. Much of this debate took part in anticipation of legislation over the "Net Neutrality", and several public consultations were lounged in 2010 (e.g. in the USA, in France and in the E.U.). Network neutrality asserts that packets should not be discriminated. Two of the important issues concerning discrimination of traffic are whether (i) an ISP may or may not request payment from a content provider in order to allow it to offer services to the local ISPs of that service provider, and (ii) whether or not a service provider can have an exclusive agreement with a given content provider resulting in a vertical monopoly. Indeed, for Hahn and Wallsten [2], net neutrality "usually means that broadband service providers charge consumers only once for Internet access, do not favor one content provider over another, and do not charge content providers for sending information over broadband lines to end users".

The Network Neutrality legislation will determine much of the socio-economic role of the Internet in the future. The Internet has already had a huge impact on economy and communication, But also on the exercise of socio-cultural and fundamental rights. Directive 2002/22/EC of the European Union, as amended by the Directive 2009/136/EC, established Internet access as a universal service[1]. The Ministry of Transport and Communication of Finland has passed a Decree in October 2009 that goes beyond the recognition of the right for Internet access: it guarantees the right for broadband Internet connection as a universal service.

The first objective of this paper is to model exclusive agreements between service and content providers and study their economic impact. Such agreements are often called "vertical monopoles". In some branches of industry, there has been legislation against vertical monopoloies. As a result, several railway companies in Europe had to split the railway infrustructure activity from the transportation activity, and the former activity was handled to another new company. For other papers that study the impact of vertical monopolies on the equilibrium behavior, see [5], [4].

Our second objective is to study the impact of collusions between local service providers on the access to content.

We do not aim in this paper to a thourough numerical analysis of the problem. Instead, we choose to study simple models that allow one to obtain explicit expressions for the equilibrium behavior which enables us to get qualitative insight on the role of model parameters on the equilibrium behavior. We thus restrict to models that have some symmetry. The study of non symmetrical is known to be harder, yet there is some evidence that the symmetric models produce the worst behavior at equilibrium, see [1], [9].

This paper is a followup of [10] in which the players were the regional ISPs and in which local ISPs were not modeled. Our results further extend the results from [10] in another aspect.

- [10] considers general costs but restricting to CPs that have exclusive agreements with rISPs,

[1]A universal service has been defined by the EU, as a service guaranteed by the government to all end users, regardless of their geographical location, at reasonable quality and reliability, and at affordable prices that does not depend on the location.

- It allows any type of ISPs and CPs (with or without exclusive agreements) but then restricts to linear models for congestion costs and utilities.

In this paper we consider a general cost model for any type of CP (with or without an exclusive relation to an ISP).

II. Model

We consider the network depicted in Figure 1 that contains regional Internet Service Providers (rISPs) Content Providers (CPs) and local ISPs (lISPs). We assume that the rISPs have a vertical monopoly: each ISP has an exclusive agreements with some CP (called super CP, or sPC). More precisely, we assume that there are n pairs of rISP - CP, where each such pair is tied together by some exclusive agreement. In particular, an rISP can own the corresponding sCP or vice versa. An example is France Telecom (ISP) which owns Daily Motion (sCP). There are in addition m independent CPs that do not have any agreement with an ISP.

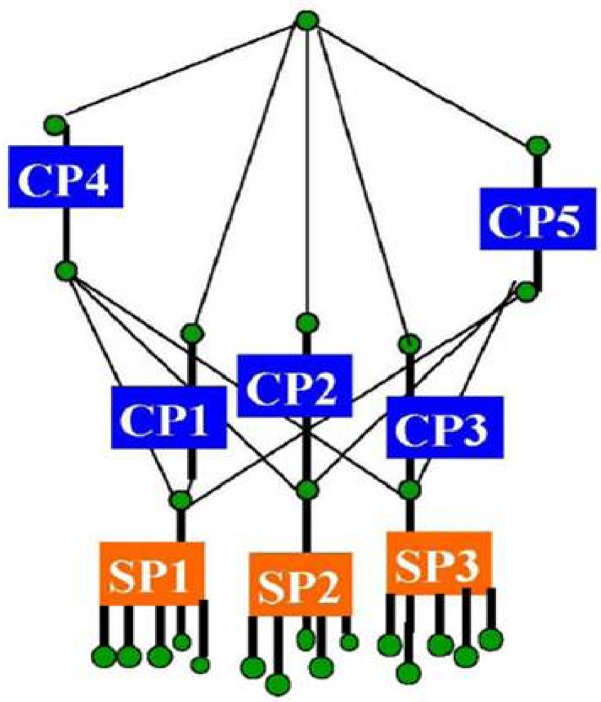

Fig. 1. Routing Game Representation of the Networking Game between nI local ISPs (small circles in the bottom of the figures) where each group of I local ISPs is connected to a regional ISP (rectangles named SP1, SP2 , SP3, in the figure). Each regionanl ISP has an exclusive agreement with some CP which we call super CP (CP1, CP2 and CP3). There are in addition m Independent Content Providers (ICP) these are CP4 and CP5 in the figure.

Through each regional ISP (which we denote by rISP) i, demand is assumed to transit to I local ISPs. We assume that each of these creates a demand for content at a rate of ϕ. All the local ISPs are assumed to be identical. We assume that the same content is available at all CPs. A local ISP k of a rISP i splits its demand between the content providers, it downloads an amount $x_j^{i,k)}$ from CP j for $j \in \{1, \ldots, n+m\}$. Let x_j be the total demand requested from CP j, i.e. $x_j = \sum_{i,k} x_j^{i,k}$. The total demand received by local ISP i, k has the flow constraint:

$$\sum_{j=1}^{n+m} x_j^{i,k} = \phi, \quad x_j^{i,k} \geq 0, \ \forall j \in \{1, \ldots, n+m\}.$$

We assume that there is a congestion cost at content provider j that is paid by each packet that is downloaded from it. This cost is assumed to be a convex increasing function of the total demand offered to the content provider. In particular, this function may represent the expected download delay per packet for traffic from the content provider. We denote the function that corresponds to the per-packet cost of content provider j by $D_{cp}^j(x_j)$.

We assume further that there is a fixed per packet cost of d_{ij} that a local ISP connected to rISP i is charged per content unit it requests from CP j. This can represent a monetary cost or an additional constant delay due to propagation. The disutility or cost function of local ISP k connected to a rISP i is given by

$$C^{i,k}(\underline{\mathbf{x}}) = \sum_{j=1}^{n} x_j^{i,k} (D_{cp}^j(x_j) + d_{ij}).$$

The aim of the paper is to study the impact of the vertical monopolies on the demand pattern among different CPs. In particular, assuming that the local ISPs are non-cooperative and that a local ISP is charged less for access to the CP associated with its own rISP, we seek to quantify the impact of the exclusive agreement on the diversity in the demand, i.e. in the amonut of demand that will be submitted to CPs that are not associated with the corresponding rISP.

We assume that d_{ij} takes three possible values. It equals Δ when the demand is for a CP associated to the rISP to which the local ISP is connected, it is d when the demand is for a CP associated to another rISP, and it is δ when the demand is for an independent CP. We further assume that D_{cp}^j are the same functions for all j, which we then often omit from the notation.

We assume that the impact of the vertical monopolies is that $\Delta < d$ and $\Delta < \delta$. This could represent the fact that rISP i provides caching to information that is fetched from its associated sCP.

III. Computing the equilibrium

In order to compute the equilibrium of this networking game, we associate a Lagrange multiplier $\lambda^{i,k}$ with local k connected to rISP i. We use it so as to relax the constraint corresponding to the total flow conservation of player i, k. Write the Lagrangian as

$$L^{i,k}(\underline{\mathbf{x}}) = C^{i,k}(\underline{\mathbf{x}}) - \lambda^{i,k}(\sum_j x_j^{i,k} - \phi),$$

where $\mathbf{x}$ is the vector of demand for all the end users of the system. Now, according to Karush-Kuhn-Tucker theorem, (under our convexity conditions) for each i, $x^{i,k} = \{x_j^{i,k}\}$ is a best response for player (i,k) if and only if there exist $\lambda^{i,k}$

such that $\lambda^{i,k}\left(\sum_j x_j^{i,k} - \phi\right) = 0$ and such that x^i minimize L^i. The best response x_j^i for player's i demand to content provider j should thus satisfy:

$$0 \leq \frac{\partial L^{i,k}(\mathbf{x})}{\partial x_j^{i,k}} = D_{cp}^j(x_j) + d_{ij} + x_j^{i,k}\frac{\partial D_{cp}^j}{\partial x_j^{i,k}}(x_j) - \lambda^{i,k} \quad (1)$$

Moreover, the above equals zero if $x_j^{i,k} > 0$.

The game is seen to be equivalent to a standard splitable routing game as studied in [6], in which each user is a source, in which there is one common destination node, and in which each ISP and CP are represented as links. The access costs d, Δ and δ are also associated to links.

The system possesses several symmetries: (I) all local ISPs of a given rISP are interchangeable, but also (II) local ISPs of different rISPs are also inerchangeable.

Similarly, if the flows sent to each CP by all users other than i are the same, then for player i, the CPs are interchangeable. These symmetric properties implies that there exists an equilibrium in the routing game which inherits also these symmetric properties, as was recently shown in [12]. We thus restrict below, without loss of generality, to a symmetric equilibria.

Let w be the equilibrium rate of traffic requested by a local ISP cononected to a rISP from the CP associated to that rISP. Let y be the amount it requests from each super CP that is not associated with that rISP, and let z be the amount it requests from each independent CP.

Assume first that at equilibrium, (w, y, z) is an interior equilibrium. We rewrite (1) while substituting for $x_j^{i,j}$ the three different values they can take (w, y, z). We thus obtain the following equations.

We have

$$w + (n-1)y + mz = \phi \quad (2)$$

Define $\rho := Iw + I(n-1)y$. This is the amount of demand requested from a super CP.

The amount of demand from an independent CP is defined by η and it satisfies at equilibrium:

$$\eta = nIz \quad (3)$$

We have also by symmetry that $\lambda = \lambda^{i,k}$ can be chosen independent of i and k.

We get from (1) by differentiating w.r.t. w:

$$0 \geq D_{cp}(\rho) + \Delta + wD'_{cp}(\rho) - \lambda \quad (4)$$

with equality if at equilibrium, $w > 0$.

Differentiating w.r.t. y we get

$$0 \geq D_{cp}(\rho) + d + yD'_{cp}(\rho) - \lambda \quad (5)$$

with strict equality holding if $y > 0$.

Finally, differentiating w.r.t. z we have

$$0 \geq D_{cp}(\eta) + \delta + zD'_{cp}(\eta) - \lambda \quad (6)$$

with strict equality if $z > 0$.

Lemma 3.1: At equilibrium, $w > y$ unless they are both 0.

Proof. The Lemma clearly holds for $y = 0$. Thus consider that at equilibrium, $y > 0$. Then we get

$$\lambda = D_{cp}(\rho) + d + yD'_{cp}(\rho) \leq D_{cp}(\rho) + \Delta + wD'_{cp}(\rho)$$
$$< D_{cp}(\rho) + d + wD'_{cp}(\rho)$$

where we used $\Delta < d$. Since $D'_{cp} > 0$ we conclude that $w > y$. ◇

Theorem 3.1: Assume that at equilibrium y is strictly positive. Then

(i) The following holds:

$$w - y = \frac{d - \Delta}{D'_{cp}(\rho)} \quad (7)$$

and we have at equilibrium

$$y = \frac{1}{n}\left(\phi - \frac{d-\Delta}{D'_{cp}(\rho)}\right), \qquad w = \frac{1}{n}\left(\phi + (n-1)\frac{d-\Delta}{D'_{cp}(\rho)}\right) \quad (8)$$

(ii) The cost at equilibrium for $d - \Delta \leq \phi D'_{cp}(\rho)$ is

$$C^{i,k} = \phi D_{cp}(\rho) + \phi\Delta + (d-\Delta)\frac{n-1}{n}\left(\phi - \frac{d-\Delta}{D'_{cp}(\rho)}\right).$$

Proof. (7) follows by combining eqs. (4) and (5). Using then the definition of ρ implies (i). We have

$$C^{i,k}(\underline{x}) = w(D_{cp}(\rho) + \Delta) + (n-1)y(d + D_{cp}(\rho))$$
$$= \phi D_{cp}(\rho) + w\Delta + (n-1)y(d - \Delta),$$
$$= \phi D_{cp}(\rho) + \phi\Delta + (n-1)y(d-\Delta)$$
$$= \phi D_{cp}(\rho) + \phi\Delta + (d-\Delta)\frac{n-1}{n}\left(\phi - \frac{d-\Delta}{D'_{cp}(\rho)}\right).$$

This establishes (ii). ◇

In the case $m = 0$, this Theorem provides a full description of the equilibrium.

Conservation of demand.

Combining (2) with the definition of ρ, we get

$$\frac{\rho}{I} + mz = \phi$$

so that

$$z = \frac{I\phi - \rho}{mI}$$

Combining with (3) we have

$$m\eta + n\rho = nI\phi \quad (9)$$

This describes the conservation of the demand as $m\eta$ is the total demand from idependent CPs, $n\rho$ is the total demand from super CPs, and $nI\phi$ is the total demand.

Computing non-trivial equilibrium

If at equilibrium $z > 0$ and $w > 0$ then we have from (4) and (6):

$$D_{cp}(\eta) + \delta + \frac{\eta}{nI}D'_{cp}(\eta) = D_{cp}(\rho) + \Delta + wD'_{cp}(\rho)$$

Substitutin the expression for η from (9) and the expression for w from Theorem 3.1, we obtain a single equation with ρ as the single unknown.

IV. Paradox and Price of Anarchy

We are interested in showing that there exist some conditions under which the behavior of the system is not as desired. For example, if the ISPs increase their cost it can result in a lower total cost for the users at equilibrium. This is a Braess type Paradox, named after Dieter Braess who first observed and computed such paradoxes in a traffic network ([7]).

We observe two types of paradoxes. The first is similar to the original Braess paradox in which eliminating a link improves the cost to all users. In our case, forcing users to download only from the CP that has a contract with their ISP can be viewed as eliminating a link. This is equivalent to taking $d = \infty$ which results in a globally optimal behavior at equilibrium.

We shall restrict below to $m = 0$ (no independent CPs). In this case the equilibrium is unique, which follows directly from [11].

Thus if $d - \Delta < \phi D'_{cp}(I\phi)$ then the equilibrium cost strictly decreases by eliminating from each ISP i the links to all CPs that except the one with which it has an exclusive agreement.

Thus there is a threshold Θ given by

$$\Theta = \phi D'_{cp}(I\phi) \tag{10}$$

such that at equilibrium, each local ISP receives all its demand from the CP associated with its rISP if and only if

$$d - \Delta \geq \Theta.$$

Another variant of Braess paradox studied in the literature consists of the impact of adding capacity to links. A paradoxical behavior is one in which the equilibrium cost increases when the capacity is increased. Translated to our model, we shall say that we have a paradox if by increasing the cost d the equilibrium cost would decrease. From the above calculations, an increase of the cost d from any value such that $d - \Delta < \phi D'_{cp}(I\phi)$ to a value satisfying $d + \Delta \geq \phi D'_{cp}(I\phi)$ creates a paradox of this kind.

However, we can identify yet another such paradox. Indeed, the local ISP cost is also decreasing whenever

$$d - \Delta \in \left[\frac{\phi D'_{cp}(I\phi)}{2}, \phi D'_{cp}(I\phi)\right). \tag{11}$$

To see that, note that the cost C^i at equilibrium is expressed by:

$$C^{i,k} = \phi D_{cp}(I\phi) + \phi\Delta + (d - \Delta)\frac{n-1}{n}\left(\phi - \frac{d}{D'_{cp}(I\phi)}\right).$$

Then the cost of a local ISP is an hyperbolic function with a maximum when

$$d = d^* := \frac{\phi D'_{cp}(I\phi)}{2} + \Delta.$$

Then as d increases, the local ISP cost at equilibrium first increases and then decreases in d, which is a Braess type paradox.

We now look at the performance of the distributed system compared to the centralized solution. The centralized solution is obtained when a central entity determine the actions to take for all users. In order to do that, we use the concept of Price of Anarchy (PoA) [8].

This metric is defined as the ratio between the maximum user cost at equilibrium and the cost for the optimal centralized problem. Our important result is that the PoA is unbounded which is not generally the case in economic problems.

Proposition 4.1: The PoA is unbounded.

a) Proof:: Take $m = 0$. The optimal local ISP cost at equilibrium, depending on d, is:

$$C^i(d^*) = \phi(D_{cp}(I\phi) + \Delta) + \frac{n-1}{n}\frac{1}{4}\phi^2 D'_{cp}(I\phi)$$

The globally optimal solution is obtained at $y = 0$ for which the local ISP cost is $\phi(D_{cp}(I\phi) + \Delta)$. Thus, the price of anarchy is given by

$$PoA = \frac{C^i(d^*)}{\phi[D_{cp}(I\phi) + \Delta]} = 1 + \frac{(n-1)\phi D'_{cp}(I\phi)}{4n(D_{cp}(I\phi) + \Delta)}$$

In particular, let $\Delta = 0$ and $D_{cp}(x) = \exp(4nsF(x)/(n-1))$ for some F. Then

$$D'_{cp}(I\phi) = 4snD_{cp}(I\phi)F'(I\phi)/(n-1)$$

so that

$$PoA = 1 + \phi s F'(I\phi)$$

Thus the PoA is unbounded: we can make it as large as we wish by choosing s sufficiently large. ■

V. Collusions and Conclusions

For the case of $m = 0$, the equilibrium demand from each CP does not depend on d, it is simply $I\phi$. This is obvious from demand conservation, since each rISP is connected to I local ISPs, each bringing a demand of content at a rate of ϕ.

If all Internauts were cooperating with each other, then each one would fetch all its demand from the CP associated with its ISP. Thus at equilibrium we would have $w = \phi, y = 0$. Due to the non-efficiency of the Nash equilibrium, some demand will go to other CPs.

Thus in spite of the fact that exclusive agreements offer local ISPs with incentives to download from one specific CP (the one that has an exclusive agreement with the local ISP's rISP), the competition between local ISPs results in an equilibrium behavior in which local ISPs also download from other CPs provided that they are not much more expensive than the one suggested by their rISP. Thus vertical monopolies do not eliminate completely diversity in the content sources.

In addition to the vertical collusion between ISPs and CPs, we may also consider horizontal collusions between local ISPs. More precisely, asssume as before that through each rISP, a demand rate of $\Phi = I\phi$ transits to the local ISPs. Assume now that $I = \ell J$ for some integers ℓ and J greater than 1, and that each group of ℓ local ISPs at of a rISP collude and become a single player. Then the total demand that transits through the rISP is unchanged, it is Φ. but now there are only $J < I$ players connected at each rISP, each one requesting a demand of $\ell\phi$ instead of ϕ. We saw that at equilibrium, each local ISP receives all its demand from the CP associated with its ISP if and only if $d-\Delta \geq \Theta$ where Θ can now be written as

$$\Theta(\ell) = \phi\ell D'_{cp}(\Phi)$$

(this follows from (10). We conclude that as local ISPs merge to larger groups, CPs will be requested to send demand to local ISPs that are connected to other other ISPs even for larger costs d. Thus the ineficiency of the equilibrium increases with such merges, resulting however in larger diversity in the CPs from which a local ISP fetches its demand.

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