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An empirical analysis of Internet providers' interconnection strategies

Nathalie Colombier

Associate Professor at the University of Rennes 1,
researcher at CREM, M@rsouin
Faculté des Sciences Economiques
7, place Hoche -CS 86514
35065 Rennes Cedex
Nathalie.Colombier@univ-rennes1.fr

Zouhaïer M'Chirgui

Associate Professor at Euromed Management, researcher at
CREM, LAREQUAD
Domaine de Luminy - BP921
13288 Marseille cedex 9
zouhaier.m'chirgui@euromed-management.com

Thierry Pénard

Professor of Economics at the University of Rennes 1,
researcher at CREM, M@rsouin,
Faculté des Sciences Economiques
7, place Hoche -CS 86514
35065 Rennes Cedex
Thierry.Penard@univ-rennes1.fr

This paper examines the structure of relationships among the major Internet service providers in order to better understand the industrial organization and interconnection strategies of these providers. We show that the network of Internet services providers exhibits a small world structure that facilitates cooperation between them (small world structure yields efficiency in terms of coordination and communication). However, the topology of the Internet is characterized by some instability related to the intense competition occurring among providers on the regional markets. Finally, we show that interconnection decisions depend on asymmetry effects, network externalities and geographical proximity.

Internet, Peering, Interconnection Agreements, Network Externalities, Asymmetry

1. Introduction

The success of the Internet can be measured by the growing number of Internet users in the world and the multitude of applications and services available to them. Yet all these applications are only possible because thousands of networks in the world are interconnected and exchange data according to a common protocol. Historically, the interconnection of these networks is based on a “best effort” principle. This is a decentralized way of routing data packets, driven by the choice of the best route to deliver these packets, but with no guarantee of service quality or priority.

Without a minimum of cooperation between Internet carriers, most of the Internet applications we know today (e-mail, Web, video, etc.) could not be supplied. Yet the booming demand for services requiring ever more bandwidth and/or a higher quality of service (video, voice over IP) creates tensions in the relationships between Internet providers. On the one hand, the new services require greater coordination or cooperation among Internet providers, in order to guarantee a better quality of service (QoS)¹. On the other hand, these new services increase competitive rivalry between Internet providers. Consequently, some providers would like to challenge the interconnection policy and the pricing of access to their networks, in order to sharpen their competitive edge and get a better return on their current and future investments. This is all the truer as these investments will multiply in the coming years, with the deployment of networks for fibre optic access (for very high-speed Internet access).

This article sets out to analyse the contractual relationships between Internet providers and assess whether they are adapted to current technological and economic challenges. Can the interconnection structure of Internet players handle the implementation of new services with a quality warranty? In other words, is the interconnection structure favourable to cooperative resource-sharing strategies that are indispensable to implement these new services? To answer these questions, this article studies the topology of the Internet network and the interconnection strategies of the major Internet players, using a database² of all observed interconnection agreements worldwide between 2005 and 2006.

The analysis of the Internet network topology is based on the theory of networks (Watts, 2003; Watts and Strogatz, 1998) and consists in studying the graph of relationships between Internet providers. Two types of topological structure have been highlighted. Firstly, the Internet network has a scale-free structure (Barabási and Albert, 1999; Faloutsos et al., 1999; Vasquez et al., 2002) and secondly, it is characterized by a small world (Barceló et al., 2004; Jin and Bestavros, 2006).

The analysis of interconnection strategies between Internet providers refers to the theory of industrial organization focusing on the trade-off between network effects and competition effects (Crémer et al., 2000). The incentives to interconnect notably depend on the degree of size asymmetry among Internet providers and the nature of the competition (Baake and Wichmann, 1999; Badasyan and Chakrabarti, 2008; Carter and Wright 2003; Foros and Hansen, 2001; Foros, Kind and Sand, 2005; Laffont et al., 2003; Jahn and Prüfer, 2004; Weiss and Shin, 2004). The empirical studies of D'Ignazio and Giovannetti (2006, 2007), Giovannetti et al., (2007) or Lippert and Spagnolo, (2007) have also revealed the importance of the proximity effects in interconnection decisions.

The originality of this article is to use these two theoretical approaches (theory of networks and theory of industrial organization) to better understand the links between Internet providers' interconnection strategies and the place they occupy in the global network. In particular, we show that only the network of operators located at the top level of the Internet has a small-world structure favourable to support

¹ Quality-of-Service (QoS) is a set of service requirements (such as bandwidth capacity, redundancy, affordability, scalability, resource contention, etc.) to be met by the network while transporting a flow.

² This data was collected by Orange, ex-France Télécom.

services with QoS guarantees. Furthermore, the Internet topology is characterized by a relative instability due to the competition between operators on providing Internet access and service at local level. Lastly, we show that the interconnection strategies depend on the scope of network effects, the degree of symmetry between Internet providers and their geographical proximity.

The article is organized as follows. Section 2 describes the structure of the relationships between Internet players. Section 3 presents the data used and offers a topological analysis of inter-operator relations. Section 4 concerns the determinants of interconnection agreements between Internet providers. Lastly, section 5 concludes.

2. The structure of internet relations

Internet is a network of interconnected IP (Internet Protocol) networks that carry data, in the form of packets, at the request of users. There is a hierarchy among Internet providers with, on the upper level, global operators, called Internet Backbone Providers (IBP), who supply the universal connectivity to the regional or local operators, who are called Internet Service Provider (ISP). An ISP cannot sell access to the Internet without establishing a minimum number of interconnection agreements, notably with one or more IBP, because it is the only way to guarantee its customers universal reachability (i.e. the ability to access all the other Internet networks).

The number of IBP is quite low, roughly twenty, and mostly American (for example Level 3, VerizonUUNET, AT&T, Sprint or PSINet). The IBP have a broad worldwide coverage and they are interconnected by means of peering agreements. In practical terms, a peering agreement is a bilateral contract under which Internet providers do not charge each other for terminating traffic. It involves the exchange of traffic on a settlement-free basis (DangNguyen and Pénard, 1998, 2000). On the other hand, the relationships between IBPs and ISPs are generally customer-supplier type relationships that take the form of *transit agreements*. The customer pays transit fees for the universal connectivity service provided by the IBP.

The ISPs are the regional operators who supply access and connectivity services to local operators or to end-users. Here again, ISPs may have two types of interconnection agreement. They can opt for peering (settlement-free) agreement. However, when the ISPs have unequal traffic flows, the peering agreement may be replaced by a paid peering agreement, where the smaller ISP has to pay transit fees, which is often fixed, to be interconnected with the larger ISP.

So Internet relationships exhibit a very hierarchical structure, with the first level (IBP) operators, also called Tier 1, who form the core network of Internet and provide the universal connectivity. Then we distinguish between the Tier 2 players (who have a regional coverage, with points of presence in several countries or continents) and the players of lower level (Tier 3), who are generally local Internet access providers, in contact with the end user.

The absence of any international regulation of interconnection agreements has largely contributed to reinforcing the hierarchical structure of Internet. The presence of very heterogeneous operators (in terms of geographic coverage or number of customers) leads to imbalances in the powers to negotiate interconnection

agreements and a gradual replacement of peering agreements by transit agreements between asymmetric operators. The growing demand for QoS has made interconnection policies even more strategic. The choice of the partners with which an operator interconnects determines the nature and the quality of the services it can offer and the cost it will have to pay. An operator may decide not to interconnect with another operator because the costs involved exceed the expected benefits, or because they are both in direct competition. In the next sections, we analyze these strategic choices through the theory of networks and the theory of industrial organization.

3. The topology of internet networks

First, we describe the database. Then we study the structural properties of the interconnected network of the top-level Internet providers, before analysing the position and the centrality of these operators.

3.1. Description of the data

The data used in this article concerns the interconnection relationships (existence of an agreement or not, and nature of the agreement, whether peering or transit) between Internet networks identified as Autonomous Systems (AS), which means networks managed by a single entity. This data has been inferred for 2005 and 2006, from BGP (*Border Gateway Protocol*) routing tables available on the open routers of the Internet. The BGP routing protocol lets each Autonomous System (AS) define the routing policies to the other Autonomous Systems. The routing policies, for instance, filter the announced routes according to the interconnection agreements signed by the AS, give preference to the choice of certain routes, or provide for backup routes to deliver a packet to a given destination. For instance an autonomous system (AS) does not forward to its peers (with which it has a peering agreement) the routes that transit through its connectivity providers (with which it has a transit agreement) so it does not have to pay its provider for traffic on which it receives no remuneration. By observing route transmissions between the AS, we can therefore infer the nature of their relations: *i*) no agreement if no route is transmitted between two AS, *ii*) existence of a peering agreement if the routes are selectively transmitted and lastly, *iii*) existence of a transit agreement if all the routes are transmitted.

Our final database contains all the interconnection agreements established by the top 100 operators or AS in terms of ranking³ between 2005 and 2006 (over an eighteen month period). An operator's rank is calculated on its customers' cone, which means the number of addresses hosted by this operator⁴. So the ranking is a good indicator of the size of a network, in terms of customers.

³ The fact of limiting it to the top 100 operators who handle the routing of over 95% of the Internet traffic gives us more reliable data on routing policies (Bailey, 1997; Gorman and Malecki, 2000). Beyond the top 100 operators, there is a higher risk of error in inferring the nature of the agreements (peering versus transit). Furthermore, the number of small AS (local) is so high (several tens of thousands) that keeping them in the database would have limited our understanding of the Internet topology at global level and would not have revealed the strategic principles of interconnection between operators.

⁴ See J. Xia and L. Gao, On the Evaluation of AS Relationship Inferences, IEEE Globecom, 2004.

Each observation corresponds to a possible pair of operators in this database. Each pair is identified by the name of the two operators linked together; the first operator is by construction the one with the highest ranking. In the case of a transit agreement (*provider-to-customer agreement*), the *provider* is the first operator and the *customer* is the second operator. In the case of a peering agreement or no agreement, the choice of the operator named first is not important. Since we are considering the top 100 Internet providers, the database is composed of 4 950 pairs (and therefore as many potential interconnection agreements). From the data collected on BGP routing, 977 agreements were identified, representing 19.74% of the potential agreements. 65% of the agreements are of peering type and 35% are of transit type.

In what follows, we seek to analyse the structure of the relationships between operators by taking their hierarchical positions into account (*Tier 1, Tier 2 or Tier 3*). As *Tier 1* (or backbones) are at the highest level, they are never customers of another operator and may be either providers, or in a peer-to-peer relationship (with operators at level 1 or lower). The *Tiers 2 or 3* in turn may provide the connectivity to other operators at the same level or lower (*provider* status), but they can also buy connectivity from operators of the same level or higher (*customer* status). More specifically, the *Tier 2* contains all providers of national services as well as the major content providers, whereas the *Tier 3* is principally local access providers and content providers.

Figure 1 shows the hierarchical structure of the Internet and Table 1 presents the breakdown of the operators or AS in our database according to their hierarchical level (*Tiers 1, 2 and 3*) for the following three periods of analysis (July 2005, January 2006 and July 2006).

Figure 1: The hierarchical structure of Internet Service Providers

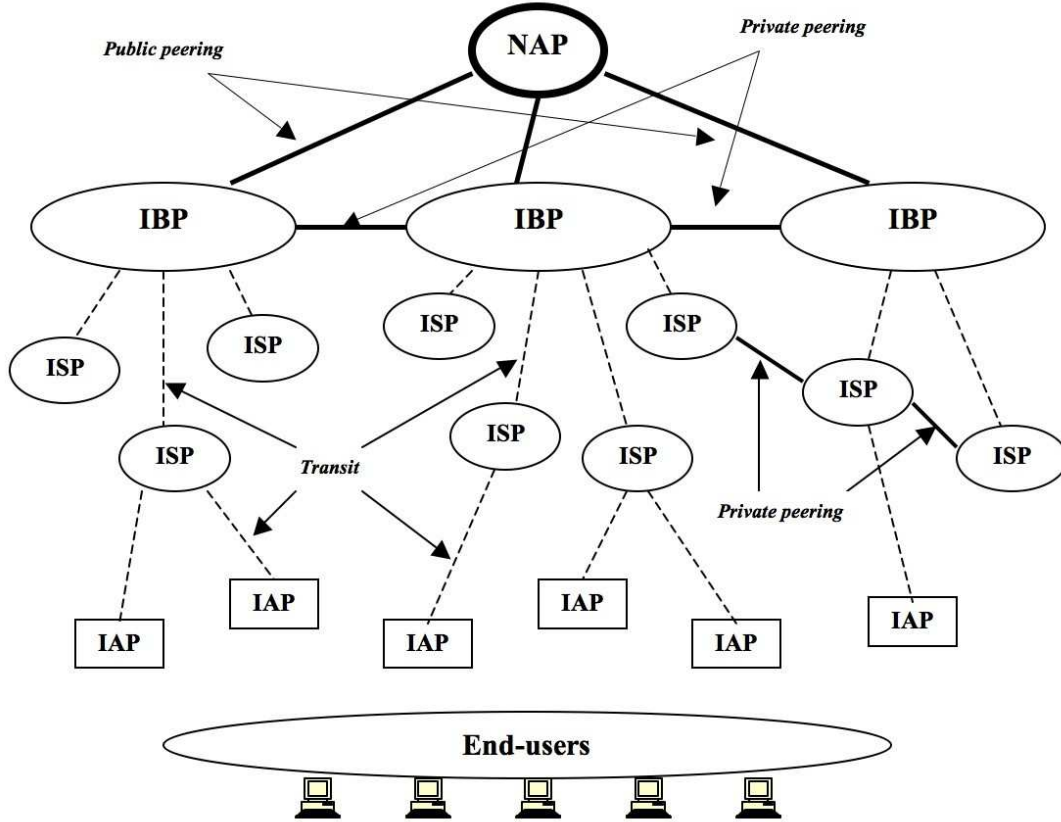


Table 1. The distribution of ISPs over the period of analysis

	2005_07	2006_01	2006_07
Tier1	13	12	19
Tier2	71	73	69
Tier3	16	15	12
Total	100	100	100

3.2. Topology of inter-operator relationships

The structure of a network (social network, physical network, etc.) can be characterized by its topological properties like the *clustering coefficient*⁵ and the *path length*⁶. Several works have shown that the Internet network displays a small

⁵ **The clustering coefficient** corresponds to the probability that two nodes connected to a third are also connected to each other. This measurement is used to assess the size of clusters in a network. In formal terms, the clustering coefficient C_i of a node is the ratio between the number of links E_i that exist between the neighbours of a node i (the latter having k_i neighbours) and the total number of possible links between these neighbours $\frac{k_i(k_i - 1)}{2}$, $C_i = \frac{2E_i}{k_i(k_i - 1)}$. The clustering coefficient of the network C is then the average value of the clustering coefficient of all the nodes.

⁶ **The path length** is the average of the shortest paths between each pair of nodes defined by $L = \frac{2}{n(n+1)} \sum_{i \geq j} d_{ij}$, with d_{ij} the shortest geodesic distance between a node i and a node j (the

world structure (high clustering and low path length)). The small world concept originated from Milgram (1967) and refers to an experiment conducted at the time that consisted in determining whether it was possible to link two individuals, randomly selected from somewhere in the United States, from their network of acquaintances. The result of this experiment, known by the term “*six degrees of separation*” showed that it was possible to link two randomly chosen people by a chain of acquaintances measuring six interpersonal relationships on average. These works were then revisited by Watts, a doctoral engineering student at Cornell University (Watts [1999], Watts and Strogatz, [1998]).

The “small world” nature of a network is empirically determined by comparing the average *path length* and the *clustering coefficient* of this network (L, C) with those of a random network (L_R, C_R) having the same number of nodes and links (Watts 2003). For a random network, the path length is measured by $L_R(n, k) \cong \ln(n)/\ln(k)$ and the clustering coefficient by $C_R \cong k/n$ for $n \gg k \gg \ln(n) \gg 1$, with n the number of nodes (players) and k the average value of the number of links⁷. A network is then characterized as a “small world” if $L \cong L_R$ (identical path length) and $C \gg C_R$ (stronger clustering than in a random network) or $(C/C_R)/(L/L_R) > 1$.

We calculate the small world properties of the Internet network, for each of the three dates (July 2005, January 2006 and July 2006). Table 2 shows the topological properties of the network of the top 100 Internet providers (in terms of rank). We also consider the network’s properties of the sub-set of Tier 1 and the subset of Tier 2 among the top-hundred Internet providers.

Table 2. Small-world characteristics for interconnection agreements

Period	Nb. of AS	Nb. of agreements	Average degree	Average path length (L)	Average path length (random) (L_R)	L/L_R	Clustering coefficient (C)	Clustering coefficient (random) (C_R)	C/C_R	Small World Coefficient
Top 100										
07/2005	100	1964	19,64	1,97	1,54	1,27	0,58	0,19	2,97	2,33
01/2006	100	1836	18,36	2,05	1,58	1,29	0,52	0,18	2,83	2,19
07/2006	100	1944	19,44	2,05	1,54	1,32	0,55	0,19	2,82	2,13
Tier 1										
07/2005	13	968	74,46	2,03	1,90	1,06	0,84	0,11	7,11	6,66
01/2006	12	798	66,5	2,05	2,03	1,01	0,86	0,10	8,33	8,23
07/2006	19	970	51,05	2,02	1,85	1,09	0,62	0,12	4,81	4,40
Tier 2										
07/2005	71	1742	24,53	2,02	1,60	1,26	0,49	0,17	2,75	2,17
01/2006	73	1680	23,01	2,11	1,64	1,28	0,44	0,16	2,65	2,06
07/2006	69	1694	24,55	2,04	1,59	1,28	0,47	0,18	2,55	1,98

Table 2 clearly indicates that the Internet network displays “small world” properties especially at the highest level (path length close to that of a random network, but much stronger clustering than in a random network). The “small

number of segments to link i to j by the shortest path) and n the total number of nodes in the network.

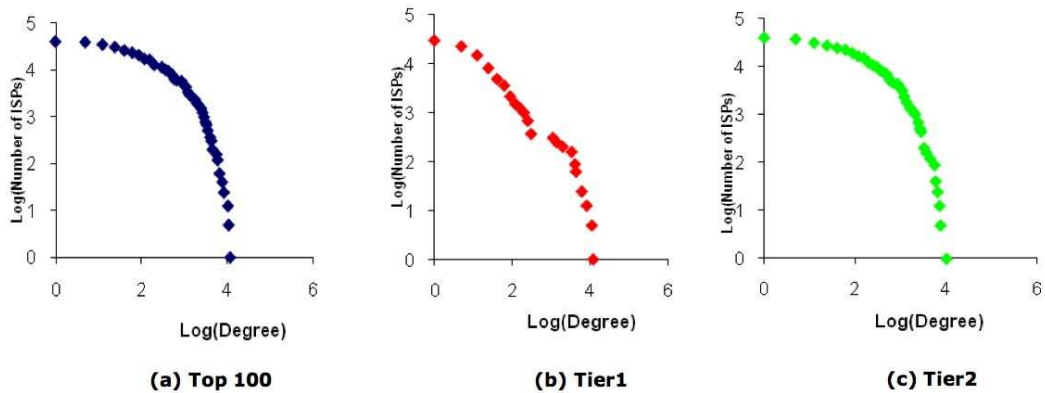
⁷ The condition $n \gg k$ presupposes a low network density; this means that there is no dominant node (or hub) to whom most of the nodes are directly connected. The condition $k \gg \ln(n)$ guarantees that the random network is connected.

world” coefficient is between 2.13 and 2.33 for the network of the top 100 operators, whereas the same coefficient is in a bracket of 4.4 to 8.3 for Tier 1 providers alone. This result can be explained by the interconnection policy of first level operators after the 1990s. With the rise in the number of service providers on the Internet and growing demands for bandwidth, the interconnection policies of the *backbones* or *Tier 1* shifted towards a more restrictive use of peering agreements with lower level operators (DangNguyen and Pénard, 2000; Buccirossi and *al.*, 2005; Frieden, 2000; Kende 2000), reducing the overall clustering of the network. Internet therefore shows a vertically differentiated topology. At the highest level, it is technically and economically necessary to be connected with a large number of peers to provide a universal connectivity service. This explains the high degree of clustering between level 1 operators. At the lower level, the operators largely rely on their transit agreements (with higher ranking operators) to offer customers a universal connectivity service, as these agreements may be replaced with interconnection agreements with their peers (operators of the same level). This explains the lower degree of clustering between level 2 operators.

We now examine the distribution of operators’ degrees to find out whether the Internet network is scale-free as Barabasi and Albert (1999) suggested. A network is scale-free if the degrees of all network nodes are distributed according to a power law. On a log-log scale, the distribution of the degrees should correspond to a straight line. With a scale-free network, the probability that a new node is connected to another node linearly depends on the number of degrees associated with this node. So the new nodes have a higher probability of connecting to nodes with a large number of degrees than to nodes with a low number of degrees. The strongly connected nodes then dominate the network topology, forming hubs that function as attraction elements for new nodes joining the network. This is called preferential attachment behaviour (Barabási and Albert, 1999).

Figures 2a, 2b and 2c show that the distribution of the degrees does not follow a power law. The relationship between the log of the number of degrees and the log of the number of operators with this degree does not correspond to a straight line. This result indicates the existence of a topology that does not respect the properties of a scale-free network. The network appears to be structured around a few super-hubs (a handful of Tiers 1) with an attraction capacity that is more than proportional to their number of links and with a large de facto market power.

Fig. 2: The log-log of the degree distribution



3.3. Centrality of Internet providers

There are a great deal of empirical works analyzing the position of players in social networks, for example, on employees' communication in a company (Buckley and Van Alstyne, 2006), developers' relationships in open source software communities (Fershtman and Gandal, 2008), inter-firm relationships within an industry (Powell *et al.*, 2005), etc. Here, we want to measure the position of the operators, in terms of centrality, within a network of the top 100 Internet providers, and at each hierarchical level. Two centrality measurements are calculated: the degree centrality and the betweenness centrality⁸. An operator's degree centrality represents the number of links (or direct ties) this actor has formed with other operators. Consequently, the actor that has the largest number of degrees is considered as a central actor and plays a key role in the network. However, an actor that has a low number of degrees is considered as isolated from the other players, and consequently plays a marginal role in the network.

The betweenness centrality corresponds to the proportion of the shortest paths connecting different pairs of operators that pass through this actor. An operator characterized by a high degree of betweenness centrality may well have a low degree centrality (directly connected to few operators), but it constitutes a bridge between several groups of operators that are not directly connected to each other. Such an operator may then have strong market power, positioned at the core of exchanges and coordination processes⁹.

The degree centrality

Table 3 shows the top 10 Internet providers in terms of degree centrality, within the network of the top 100 operators, in July 2005, January 2006 and July 2006. Only LEVEL3 (tier 1), ABOVENET (tier 1), PSINET (tier 1) and HURRICANE

⁸ Appendix A gives the formula to calculate the different centrality measurements.

⁹ We have also run similar analyses based on closeness centrality (Freeman, 1979). While degree centrality only measures the number of direct links an operator holds, closeness centrality also considers indirect links (which are not directly connected to this actor). The results obtained for the closeness centrality are almost identical to those for the degree centrality (same ranking for the top ten operators). We have therefore chosen to only present the degree centrality to measure the market power of each operator in terms of number of relationships and the betweenness centrality to measure market power in terms of positions within the network.

(tier 2) are constantly present. This reveals volatility or instability in the operators' positions. LEVEL3 nonetheless appears to have a central role in the interconnection relationships between 2005 and 2006. It features among the top 10 operators both in terms of degree and betweenness centrality, over all the periods.

Table 4 only shows the top 10 operators of Tier 1. The positions are slightly more stable at this hierarchical level, with LEVEL3, VERIO, TELIANET, COLT and TELEGLOBE present on the three dates. Lastly, Table 5 displays the top 10 operators of Tier 2 and shows a strong instability in the positions, with only HURRICANE and INTERROUTE present on the three dates.¹⁰

Table 3. Degree centrality for Top 100

July 2005	Degree	January 2006	Degree	July 2006	Degree
SWISSCOM (tier2)	61	PSINET (tier1)	59	PSINET (tier1)	64
ABOVENET (tier1)	57	COLT (tier1)	57	CAIS-ASN (tier2)	54
LEVEL3 (tier1)	56	ABOVENET (tier1)	56	ABOVENET (tier1)	54
PSINET (tier1)	56	LEVEL3 (tier1)	50	TDC (tier2)	52
VERIO (tier1)	53	HURRICANE (tier2)	49	LEVEL3 (tier1)	49
SPRINTLINK (tier1)	51	INTERROUTE (tier2)	46	HURRICANE (tier2)	46
HURRICANE (tier2)	49	KPN (tier2)	44	VERIO (tier1)	45
REACH (tier2)	44	TELIANET (tier1)	43	TELIANET (tier1)	45
LAMB DANET-AS (tier2)	44	TELENOR (tier2)	43	KPN (tier2)	43
CAIS-ASN (tier2)	43	TELECOMPLETE (tier2)	39	GBLX (tier2)	43

*** Operators present on the three periods are in bold**

Table 4. Degree centrality for Tier 1

July 2005	Degree	January 2006	Degree	July 2006	Degree
ABOVENET (tier1)	57	PSINET (tier1)	59	LEVEL3 (tier1)	49
PSINET (tier1)	56	COLT (tier1)	57	VERIO (tier1)	45
LEVEL3 (tier1)	56	LEVEL3 (tier1)	50	TELIANET (tier1)	44
VERIO (tier1)	53	TELIANET (tier1)	44	TELEGLOBE (tier1)	41
SPRINTLINK (tier1)	51	DEUTSCHE TELEKOM (tier1)	38	SPRINTLINK (tier1)	36
TELIANET (tier1)	41	SPRINTLINK (tier1)	38	COLT (tier1)	30
COLT (tier1)	40	VERIO (tier1)	37	PORT80 (tier1)	30
TELEGLOBE (tier1)	38	TELEGLOBE (tier1)	34	SEABONE-NET (tier1)	29
ALTERNET (tier1)	37	CWUSA (tier1)	34	SINGTEL-AS-AP (tier1)	29
AS702 (tier1)	35	ATT-INTERNET4 (tier1)	32	CWUSA (tier1)	27

*** Operators present on the three periods are in bold**

Table 5. Degree centrality for Tier 2

July 2005	Degree	January 2006	Degree	July 2006	Degree
SWISSCOM (tier2)	61	HURRICANE (tier2)	49	TDC (tier2)	52
HURRICANE (tier2)	49	INTERROUTE (tier2)	46	HURRICANE (tier2)	46
LAMB DANET (tier2)	44	KPN (tier2)	44	KPN (tier2)	43
REACH (tier2)	44	TELENOR (tier2)	43	CAIS-ASN (tier2)	41
CAIS-ASN (tier2)	43	TELECOMPLETE (tier2)	39	KDDI (tier2)	39

¹⁰ The graph of the operators' relationships is presented in appendix.

*** Operators present on the three periods are in bold**

The betweenness centrality

Tables 6, 7 and 8 show the top ten Internet providers in terms of betweenness centrality on the whole network, and on the network limited to level 1 providers and to level 2 providers. The results are relatively similar to those obtained beforehand in Tables 3, 4 and 5. The betweenness centrality is closely correlated to the degree centrality. Consequently, 80% of the Internet providers listed in Table 3 appear in Table 6. Similarly, 93% of the Internet providers present in Table 4 are also in Table 7. Lastly, 73% of the Internet providers listed in Table 5 are present in Table 8. Table 9 presents the value of the correlation coefficients between degree centrality and betweenness centrality for the different dates. The coefficients are all higher than 0.744. These results show that the most connected players (degree centrality) are also those who act as intermediaries in the network, giving them real market power. However, the high instability in Internet providers' ranking over time, even at the top level, is more the sign of competitive market structure. No actor appears to dominate the interconnection relationships. This is in line with the conclusions of Economides (2006) on the highly competitive nature of the Internet at the top level.

The originality of this topological analysis of the Internet network is to reveal the dual structure of the Internet, with a network with strong small world-type clustering at the upper level, and a network with weaker connections and more instability at the lower level. These results are confirmed when we examine the assortativity of these networks, which consists in seeing whether the players with the largest number of links tend to connect to each other. For this purpose, we calculated the Pearson correlation coefficient generally used to measure assortativity (Newman, 2002). The results show that the network is assortative, as the Pearson correlation coefficient is positive. This means that the Internet providers with a high degree centrality are primarily connected to other Internet providers with a high degree centrality too, these relationships creating a situation of collective domination of the Internet.

Table 6. Betweenness centrality for Top 100

July 2005	Coefficient	January 2006	Coefficient	July 2006	Coefficient
SWISSCOM (tier2)	382.22	TELIANET (tier1)	439.06	PSINET (tier1)	311.50
LEVEL3 (tier1)	375.48	LEVEL3 (tier1)	349.67	LEVEL3 (tier1)	296.52
VERIO (tier1)	352.57	COLT (tier1)	341.77	KDDI (tier2)	292.49
SPRINTLINK (tier1)	344.25	INTERROUTE (tier2)	282.56	TDC (tier2)	272.15
HURRICANE (tier2)	253.61	PSINET (tier1)	268.47	ASCC-AS-AP (tier2)	243.13
LAMBDANET-AS (tier2)	248.29	HURRICANE (tier2)	244.58	SEABONE-NET (tier1)	220.87
PSINET (tier1)	227.48	ABOVENET (tier1)	237.97	VERIO (tier1)	220.28
ABOVENET (tier1)	219.30	SPRINTLINK (tier1)	199.61	CAIS-ASN (tier2)	211.85

TISCALI-BACKBONE (tier2)	187.95	Deutsche Telekom (tier1)	177.00	GBLX (tier2)	186.40
REACH (tier2)					177.34

*** Internet providers present on the three periods are in bold**

Table 7. Betweenness centrality for Tier1

July 2005	Coefficient	January 2006	Coefficient	July 2006	Coefficient
LEVEL3 (tier1)					
SPRINTLINK (tier1)					
ABOVENET (tier1)					
VERIO (tier1)					
PSINET (tier1)					
ALTERNET (tier1)					
COLT (tier1)					
TELIANET (tier1)					
TELEGLOBE (tier1)					
AS702 (tier1)					

*** Internet providers present on the three periods are in bold**

Table 8. Betweenness centrality for Tier2

July 2005	Coefficient	January 2006	Coefficient	July 2006	Coefficient

*** Internet providers present on the three periods are in bold**

Table 9. coefficients of correlation degree/betweenness

	July 2005	January 2006	July 2006
TOP 100	0,834	0,800	0,744
Tier 1	0,925	0,908	0,786
Tier 2	0,826	0,808	0,786

In what follows, we will examine the motivations for interconnecting and identify the determinants of peering and transit agreements.

4. The determinants of interconnection agreements

Interconnection decisions depend on efficiency considerations, as well as strategic considerations¹¹. Based on these considerations, we formulate several

¹¹ Other considerations may also intervene such as the regulatory obligations applying to operators, which may vary between countries, but this article does not cover these.

hypotheses about the factors that may increase or decrease the incentives to interconnect.

4.1. Efficiency motives

Efficiency considerations refer to the benefits of interconnection. The interconnection agreements allow an operator to improve its coverage and quality of service, by using part of its partner's network. Without interconnection, Internet providers would be unable technically to provide most of the existing service applications to their customers or to supply them under economically viable conditions. The benefits of interconnection may be measured as direct or indirect gains. The indirect gains correspond to investment amounts saved (in terms of geographical coverage) and the possibility of charging customers more for higher quality services. In case of transit agreements, the provider also receives a direct gain from interconnecting, in the form of transit fees from the client operator.

However, interconnection does generate direct and indirect costs. Firstly, the operator has to pay to access the exchange nodes where it will interconnect with its partners, and each new interconnection agreement will generate costs for activating and maintaining the connection. The operator will then have to resize its network to handle its partners' traffic, in order to avoid any congestion or deterioration in quality of service to its own customers.

The extent of the gains and costs generated by an interconnection agreement will depend, among others, on the respective size of the two Internet providers, their geographic coverage and their bandwidth (Besen et al., 2001; Milgrom et al., 2000; Jahn and Prüfer 2008; Weiss and Shin, 2004). Three cases may occur. If the gains exceed costs for both Internet providers, a peering agreement is then possible (as this agreement is mutually beneficial). If only one of the two Internet providers has a gain exceeding the costs of interconnection, an agreement is then possible, although in the form of a transit agreement rather than a peering agreement (if the operator with a positive net gain agrees to pay a transit fees to the other operator, which then becomes its provider). Lastly, if both Internet providers have interconnection costs that exceed their gains, no agreement should be entered into.

The principal mutual benefits of interconnection for Internet providers are to stimulate network externalities, which have the effect of increasing customers' satisfaction and hence their willingness to pay for the services proposed by these Internet providers. An operator can offer customers better quality of access to the customers and services of partner operators through its interconnection policy (Crémer et al., 2000). So network effects and the incentives to interconnect should be even stronger when the cumulative size of the two networks is large.

Hypothesis 1: the probability of entering into an interconnection agreement should rise with the combined size of both networks.

Geographical proximity can also play an important role in interconnection decisions, by increasing the network effects (denser traffic flow) and by reducing interconnection costs (D'Ignazio and Giovannetti, 2006, 2007). An interconnection decision, particularly a peering agreement, requires a high level of trust and informal cooperation between the Internet providers to manage uncertainty and contractual incompleteness (Schumacher, 2006; Giovannetti et al., 2007). Geographical proximity may facilitate this trust (Beamish and Banks, 1987; Hennart and Reddy,

1997). According to transaction cost theory, the cost of monitoring and auditing partners decreases when the partners are geographically close. The degree of uncertainty is also lower when the networks operate work in a similar business and institutional environment.

Hypothesis 2: the probability of entering into an interconnection agreement should increase in case of geographical proximity.

4.2. Strategic motives

While the Internet providers generally have a common interest in interconnecting to improve their quality of service and to lower their investment costs, they may refrain from doing it for strategic reasons. The first reason is the risk of opportunist behaviours, particularly in the context of peering agreements. One of the Internet providers may decide to under-invest in its network and thus adopt “free-rider” behaviour, by making excessive use of its partner’s network to improve the quality of its own services. If it is interconnected with another operator at several points, it may be tempted to forward the packets addressed to the latter’s customers as soon as possible so that its partner has to bear most of the transport costs (*hot potato* principle). In this way, the Internet provider makes substantial savings on bandwidth investments, particularly as it uses its partner’s capacities free of charge in the peering context (Dewan *et al.*, 2000; Manenti, 2000).

However, Internet providers are less tempted to adopt this type of opportunist behaviour when they are in a relationship with operators of the same size, with the size of an operator measured by the number of interconnection agreements, its tier, its volume of traffic, its Internet access revenue, the number of accessible addresses and the number of points of presence (Carter and Wright, 2003). For example, Weiss and Shin (2004) show that the Internet providers prefer to establish peering agreements with operators who have similar traffic volumes and to propose transit agreements to smaller operators, to protect themselves against free-riding.

Hypothesis 3: the probability of entering into a peering agreement (resp. a transit agreement) should decrease (resp. increase) with the asymmetry of networks

The second reason that may cause Internet providers to refuse to interconnect is due to competition for providing connectivity service and Internet access. So it is possible that two operators of similar size refuse to do peering, because they are direct competitors and they want to differentiate their services. Interconnection effectively makes their offers more similar in terms of quality, and hence interchangeable, which may reduce their market power (Baake and Wichmann, 1999; Foros and Hansen, 2001; Foros and Kind, 2000).

Hypothesis 4: the probability of entering into an interconnection agreement should decrease when the networks are in direct competition with each other.

4.3. Methodology

The interconnection decisions can be modelled as binary choices. We estimate the determinants of interconnection strategies using a bivariate Probit model, where the decision to choose between a peering agreement and a transit agreement is

conditional on the decision to interconnect. Appendix C presents the estimated model in detail.

We have thus created the dependent variable $agreement_{i,j}$, that equals 1 if the two operators i and j choose to interconnect regardless of the nature of the agreement and 0 otherwise¹². We have also created the variable $peer_{i,j}$ that is equal to 1 if the two operators choose to conclude a peering agreement rather than a transit agreement.

For the independent variables, we have tried to find a good proxy to measure asymmetry, competition and network effects. The *diffagreement* variable is the difference (in absolute value) between the number of interconnection agreements of operator i (regardless of the type of agreement) and the number of agreements of the operator j . This variable allows us to measure the degree of asymmetry between operators, in terms of centrality in the network, and thus to measure the potential conflicting interests to sign an interconnection agreement (Hypotheses 3 and 4).

The *sumagreement* variable is the cumulative number of agreements of the two Internet providers. This variable measures the scope of network externalities and therefore the expected value of an interconnection agreement (Hypothesis 1).

In exactly the same way, the *diffpeer* and *sumpeer* variables respectively represent the difference (in absolute value) in the number of peering agreements between the two Internet providers, and the cumulative sum of the peering agreement. Lastly, *diffprovider* and *sumprovider* correspond to the different and the sum of the transit-type agreements.

Furthermore, the degree of asymmetry between the Internet providers is also measured by the relationship between the ranking of the largest operator and the ranking of the smaller operator (*asrank*). The ranking is a measurement of an operator's size, since it is calculated on the basis of the number of customers or addresses attached to this network. This variable should have a positive effect on transit agreements and a negative effect on peering agreements (Hypothesis 3).

We have also created the *astier* variable, which takes the value 1 if the two Internet providers belong to the same hierarchical level (tier 1, tier 2, tier 3) and 0 otherwise. Operators of the same level should be incited to practice peering (Hypothesis 3), but they might also decide not to interconnect to better differentiate their services (Hypothesis 4).

Finally, we test hypothesis 2 about the impact of geographic proximity by introducing the *ascountry* variable which equals 1 when the two Internet providers have the same nationality (in terms of head office and/or principal place of business) and *ascontinent* which is worth 1 if their principal activities are on the same continent.

The econometric estimations of the bivariate probit model on the choice of interconnecting and on the nature of the interconnection agreement were made on the most recent database (July 2006). Due to some incomplete data, the base contains 4851 pairs of Internet providers with or without interconnection agreements.

¹² The operator i has the highest ranking of the two.

4.4. Results

The results are presented in Table 10. The columns 1 and 3 present the estimations on the choice of interconnecting, whereas columns 2 and 4 correspond to the estimations on the choice of interconnection methods (peering or transit), conditional on the existence of an agreement. The results for the first specification reveal a positive and significant impact of **network externalities** on the probability of interconnecting in general, and more specifically in the form of peering agreement. Indeed the cumulative number of agreements (*sumagreement*) has a positive and significant effect on the probability of concluding an agreement and choosing a peering agreement.

The degree of asymmetry in the number of interconnection agreements between two Internet providers reduces the incentives to interconnect. Moreover, conditional to an agreement, the asymmetry increases the probability of signing a transit agreement, in accordance with hypothesis 3. The fact of being two Internet providers of the same tier (*astier*) also increases the probability of interconnecting by means of peering agreement. Moreover, the probability of agreement is greater in case of geographic proximity (*ascountry* and *ascontinent*). Lastly, the asymmetry in terms of ranking negatively impacts the probability of interconnecting, and more specifically by peering, in accordance with Hypothesis 3.

In a second specification, we estimated the probabilities of interconnecting and of concluding a peering or transit agreement, by breaking down the *combined network effect* and *network asymmetry effect* into a peering effect and a transit effect (by replacing *sumagreement* with *sumpeer* and *sumprovider* on the one hand, and *diffagreement* with *diffpeer* and *diffprovider* on the other hand). The estimations confirm the previous results: the network effects of the cumulative peering and transit agreements combine to increase the probability of interconnecting, whereas the degree of asymmetry in the peering and transit agreements has the same negative impact on the decision to interconnect. However, the network effects generated by peering agreements principally play on the decision to interconnect by peering, while the network effects due to transit agreements strengthen the incentives to interconnect by transit. Furthermore, the results underline a positive and significant impact of asymmetry in the number of peering agreements on the probability of signing a transit agreement.

Table 10. Bivariate Probit on the decision to interconnect and the nature of the interconnection agreement (peering versus transit)

	(Specification 1)		(Specification 2)	
	1 <i>agreement</i>	2 <i>peering</i>	3 <i>agreements</i>	4 <i>peering</i>
<i>sumagreement</i>	0.047 (0.001)***	0.050 (0.002)***		
<i>diffagreement</i>	-0.016 (0.002)***	-0.020 (0.002)***		
<i>asrank</i>	-0.063 (0.034)*	-0.183 (0.042)***	-0.065 (0.035)*	-0.134 (0.043)***
<i>ascountry</i>	0.249 (0.075)***	0.135 (0.084)	0.234 (0.074)***	0.134 (0.082)
<i>ascontinent</i>	0.255	0.326	0.239	0.205

	(0.057)***	(0.065)***	(0.057)***	(0.064)***
astier	0.121	0.349	0.191	0.249
	(0.052)**	(0.060)***	(0.056)***	(0.063)***
sumpeer			0.052	0.060
			(0.002)***	(0.002)***
diffpeer			-0.022	-0.030
			(0.002)***	(0.003)***
diffprovider			-0.022	-0.030
			(0.010)**	(0.010)***
sumprovider			0.057	0.029
			(0.008)***	(0.008)***
constant	-2.815	-3.297	-2.579	-2.849
	(0.095)***	(0.120)***	(0.094)***	(0.113)***
Observations	4851	4851	4851	4851
Log-Likelihood	-2139.1798	-2139.1798	-2078.2573	-2078.2573

ⁱ **Note : standard errors in brackets, *, **, *** coefficients**

significant at the threshold of 10%, 5% and 1% respectively.

Table 10 aims to identify the determinants of an interconnection agreement, by implicitly supposing that the decision to interconnect results from a discussion or bilateral negotiation between two Internet providers based on expected gains and costs. Yet it is undoubtedly more reasonable to consider that the largest Internet provider of the two has the power to decide whether or not an agreement will take place and the nature of that agreement. In that case, the decision will depend solely on this operator's gains and costs. Instead of taking into account the cumulative sum of the operators' agreements, it may be preferable to only consider the size of the smallest operator, which reflects the value of the network externalities that the larger operator may gain from an interconnection agreement. We have therefore introduced the *nbagreement2* variable in the first specification of Table 11, which indicates the number of agreements that the smallest operator has concluded. In the second specification, we have instead introduced *nbpeer2* which represents the number of peering agreements and *nbprovider2* the number of transit agreements concluded by the smallest operator.

We also saw in Table 10 that a difference in the number of agreements (*diffagreement*) had a negative and significant impact on the probability of interconnecting. However, it is not clear that the contrary, a minimal difference between the two Internet providers, leads to a high probability of agreement. Indeed, a competition effect may offset this symmetry effect and reduce the probability of agreement between two relatively similar Internet providers. Consequently, it is not certain that the relationship between the degree of asymmetry and the probability of agreement is linear and decreasing. In order to test non linear effects, a *diffagreementsquared* variable ($diffagreement \times diffagreement$) is introduced in the first specification in Table 11. The *diffpeersquared* and *diffprovidersquared* variables are taken into account in the second specification in an identical manner.

The results support the existence of *competition* effects that oppose the *symmetry* effect. Although the *diffagreement* variable has a positive and significant impact, the variable squared (*diffagreementsquared*) has a negative and significant impact, which indicates an inverted-U-shaped relationship between the degree of asymmetry of Internet providers and the probability of making an agreement, regardless of the

nature of the agreement. So the probability of making an agreement increases with the difference in terms of number of agreements between the two Internet providers, which supports the hypothesis of a *competition effect*. But, the incentives to interconnect decrease above a certain level of asymmetry. This turning point is not identical depending on the type of agreement. The turning point is located at a difference of 20 agreements for an interconnection decision, at 10 for a peering agreement, and at 33 for a transit-type agreement.

The other results show that the size of the smallest operator plays positively on the decision to interconnect in both peering and transit. This shows that the network externalities perceived by the largest operator constitute a key element in the negotiation process of this type of agreement. Moreover, the geographic proximity also increases the probability of interconnecting. Finally, proximity in terms of rank or hierarchical level increases the probability of interconnecting.

Table 11. Bivariate Probit on the decision to interconnect and the nature of the interconnection agreement (peering versus transit)

	(Specification 1)		(Specification 2)	
	1 <i>agreement</i>	2 <i>peering</i>	3 <i>agreement</i>	4 <i>peering</i>
nbatment2	0.042 (0.002)***	0.042 (0.002)***		
diffagreement	0.013 (0.005)**	0.014 (0.006)**		
diffagreementsquared	-0.000 (0.000)	-0.000 (0.000)**		
asrank	0.101 (0.030)***	-0.013 (0.038)	-0.003 (0.035)	-0.010 (0.043)
ascountry	0.306 (0.069)***	0.208 (0.076)***	0.221 (0.070)***	0.113 (0.076)
ascontinent	0.182 (0.052)***	0.200 (0.057)***	0.236 (0.053)***	0.222 (0.058)***
Astier	0.124 (0.047)***	0.297 (0.053)***	0.363 (0.053)***	0.424 (0.058)***
diffpeer			0.001 (0.006)	0.002 (0.007)
diffprovider			0.103 (0.013)***	0.085 (0.015)***
nbpeer2			0.045 (0.002)***	0.047 (0.002)***
diffpeersquared			-0.000 (0.000)	-0.000 (0.000)
nbprovider2			0.014 (0.007)**	0.022 (0.007)***
diffprovidersquared			-0.003 (0.001)***	-0.003 (0.001)***
Constant	-2.159 (0.086)***	-2.405 (0.102)***	-2.130 (0.092)***	-2.376 (0.104)***
Observations	4851	4851	4851	4851
Log-Likelihood	-2575.3237	-2575.3237	-2502.6102	-2502.6102

ⁱ **Note: standard errors in brackets, *, **, *** coefficients significant at the threshold of 10%, 5% and 1% respectively.**

5. Conclusion

In this article we have shown that the current structure of the Internet reflects a coexistence of complementarities and competition between Internet providers. This explains the differentiated nature of the network according to hierarchical levels. The highest level (Tier 1 Internet providers) shows a greater degree of cohesion and stability than the lower levels. This result may be interpreted as a sign of a higher market power for providers of universal connectivity services (*backbones*) than for providers of Internet access and regional providers.

$$\text{Log}L = \sum_{ij=1}^n [(1 - y_{1ij}) \ln P_0 + y_{1ij} y_{2ij} \ln P_{11} + y_{1ij} (1 - y_{2ij}) \ln P_{10}]$$

Our results also suggest that a revision of interconnection strategies is undoubtedly necessary to provide new services with a quality warranty and to move towards a network with more cohesion between different hierarchical levels, in order to reduce the coordination costs (technical and financial) and the transaction costs that may prove very high for these kinds of services. Indeed, a “small world” network structure seems particularly suited to implement differentiated services with quality of service: **high clustering** lowers the risks of opportunism in inter-operator relationships (greater cooperation and trust between players, better monitoring of each player’s behaviour) and a **low path length** allows a better control of quality of service (easier coordination, because fewer players are involved in providing the end-to-end service).

Further analysis may be needed to distinguish Internet providers according to the nature of their activities. For instance, some operators are only transit providers, while others are just access providers, or simply content providers like Yahoo or Google. Furthermore, the operators may also be vertically integrated and appear on different hierarchical levels of the Internet. The players’ business models also differ greatly depending on their activity and the interconnection agreements do not occupy the same place in these business models. Content providers have little interest in increasing their level of centrality, whereas integrated transit and Internet access providers can take advantage of an intermediary position in the network. A better characterization of Internet providers would reveal the complexity of relationships between Internet players.

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APPENDIX A: The centrality indexes

The measurement of the degree centrality C_D of Freeman (1979) is formally defined as the sum of the number of contiguities for a node j $C_D(j) = \sum_{i=1}^n a(i,j)$, where $a(i,j) = 1$ if i and j are connected by a link; otherwise $a(i,j) = 0$. We can obtain a relative measurement of the degree centrality for a point j :

$$C_D^i(j) = \frac{\sum_{i=1}^n a(i,j)}{n-1}$$

where $n-1$ is the maximum number of nodes to which a node j could be connected.

The betweenness centrality is defined by:

$$C_B(j) = \sum_i \sum_{i < k} \frac{g_{ik}(j)}{g_{ik}}$$

where n is the number of nodes in a graph, g_{ik} is the number of geodesics connecting i and k and $g_{ik}(j)$ is the number of geodesics connecting i and k and which also contain the node j . The relative measurement of the betweenness centrality is then given by:

$$C_B^i(j) = 2 \sum_i \sum_{i < k} \frac{g_{ik}(j)}{g_{ik}} \frac{1}{(n^2 - 3n + 2)}$$

ANNEXE B

Figures 3, 4 et 5 show graphs of interconnection agreements respectively for the top 100 Internet providers, the sub-set of Tier 1 and the sub-set of Tier 2. Graphs show the density of the interconnection agreements and the positions of the different Internet providers in this network.

Figure 3: Top 100 network (July 2006)

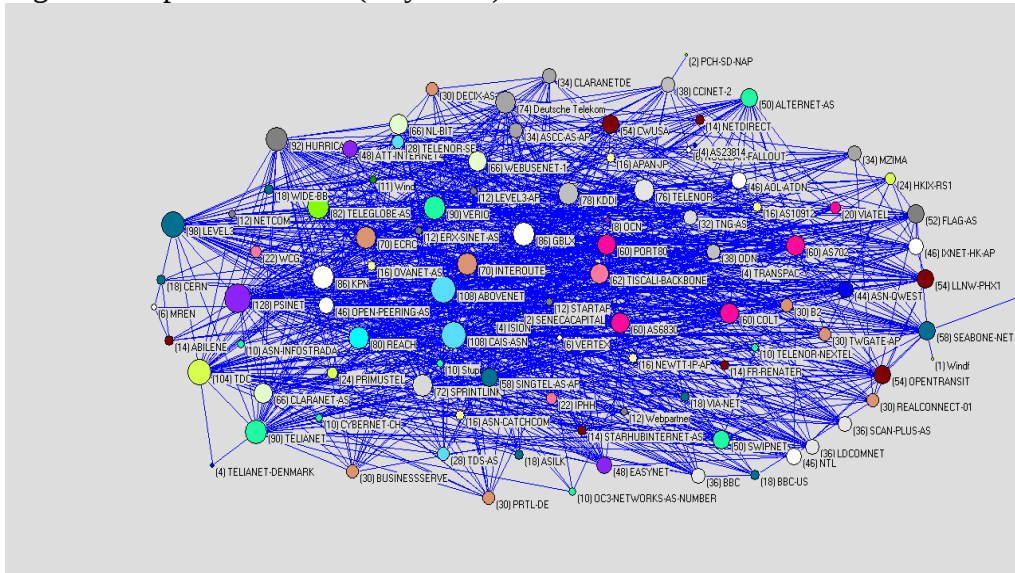


Figure 4: Tier1 network (July 2006)

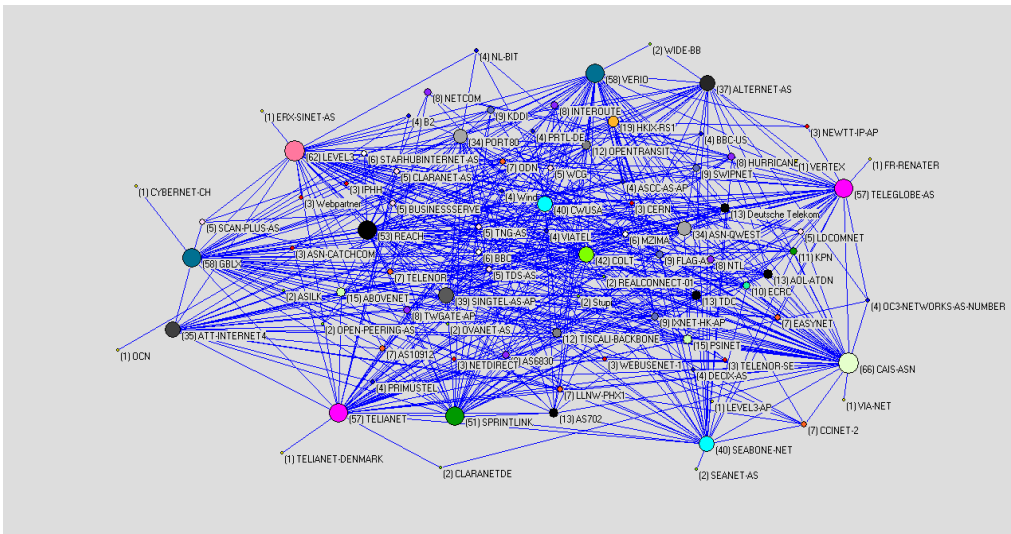
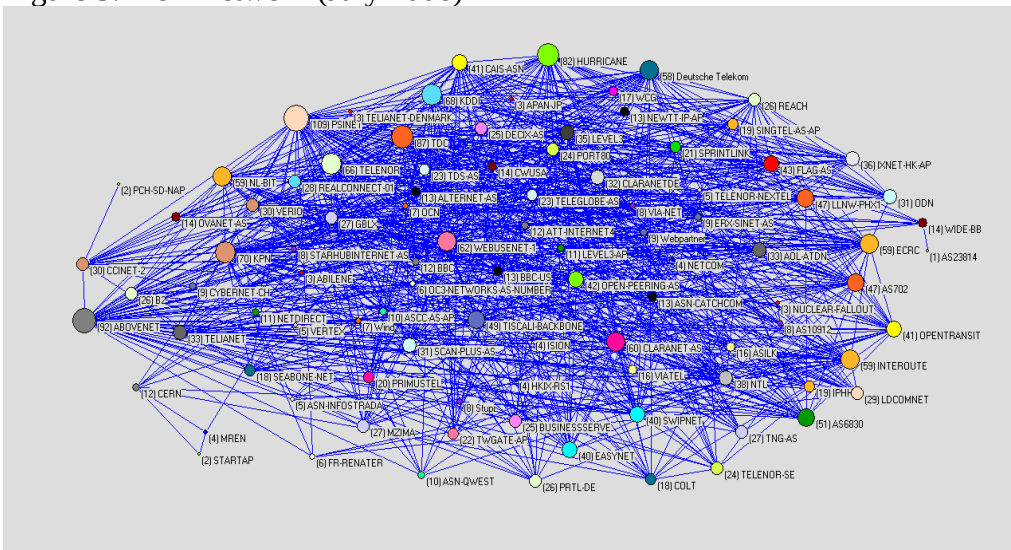


Figure 5: Tier2 network (July 2006)



APPENDIX C: The estimation method of a bivariate probit

The interconnection decisions are estimated by a bivariate Probit model, where the decision to opt for a peering agreement rather than a transit agreement is conditional on the decision to interconnect.

Let us consider that the operators i and j (the observation unit being the pair of operators) will choose to be interconnected ($y_{1ij}=1$) if $y_{1ij}^* = x_{1ij}\beta_1 + \varepsilon_{1ij} > 0$ with x_{1ij} a set of variables measuring the economic and strategic gains of interconnecting for the two operators and ε_{1ij} the normally distributed error term. Furthermore, the operators i and j will choose a peering agreement ($y_{2ij}=1$) if $y_{2ij}^* = x_{2ij}\beta_2 + \varepsilon_{2ij} > 0$ with x_{2ij} a set of variables measuring the economic and strategic gains of choosing a peering agreement for the two operators and ε_{2ij} the normally distributed error term.

Consequently, the probabilities of not interconnecting (P_0), of choosing a peering agreement (P_{11}) or a transit agreement (P_{10}) can be modelled as follows:

$$P_0 = P(y_{1ij} = 0) = P(x_{1ij}\beta_1 + \varepsilon_{1ij} \leq 0) = \int_{-\infty}^{-x_{1ij}\beta_1} \phi(\varepsilon_{1ij}) d\varepsilon_1$$

$$P_{11}(y_{2ij} = 1) = P(x_{1ij}\beta_1 + \varepsilon_{1ij} > 0, x_{2ij}\beta_2 + \varepsilon_{2ij} > 0) = \int_{-x_{1ij}\beta_1}^{+\infty} \int_{-x_{2ij}\beta_2}^{+\infty} \phi_{12}(\varepsilon_{1ij}, \varepsilon_{2ij}) d\varepsilon_1 d\varepsilon_2$$

$$P_{10}(y_{2ij} = 0) = P(x_{1ij}\beta_1 + \varepsilon_{1ij} > 0, x_{2ij}\beta_2 + \varepsilon_{2ij} \leq 0) = \int_{-x_{1ij}\beta_1}^{+\infty} \int_{-\infty}^{-x_{2ij}\beta_2} \phi_{12}(\varepsilon_{1ij}, \varepsilon_{2ij}) d\varepsilon_1 d\varepsilon_2$$

where ϕ and ϕ_{12} are respectively the functions of density ε_1 and joint density of $(\varepsilon_1, \varepsilon_2)$.

The estimated coefficients maximize the log-likelihood function given by:

$$\text{Log}L = \sum_{ij=1}^n [(1 - y_{1ij}) \ln P_0 + y_{1ij} y_{2ij} \ln P_{11} + y_{1ij} (1 - y_{2ij}) \ln P_{10}]$$