Digital communications and the role of distance

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Introduction

Part of our overall research project on "Complexity in Spatial Dynamics", which aims to:

- generate a long overdue typology of urban dynamic processes
- represent ways in which actions and interactions measured as flows on networks
- explore the properties of these processes and define typical signatures of these dynamics in terms o f scaling, hierarchies, entropy and diversity
- measure flows using new sources of data, acquired remotely, some in real- time, from ticketing, mobile and fixed line telephone calls, IP communications, etc
- develop a series of model demonstrators of these urban dynamics

Introduction

A continuation of our research on the geography of the *Internet infrastructure* in Europe, which includes:

- An analysis of the urban roles and relations due to the Internet backbone networks
- An explanatory study of the spatial distribution of the Internet backbone networks
- A topological analysis exploring the complex nature of this infrastructure
- A study evaluating the causal effects of the Internet infrastructure on the economic development of the European city-regions

Outline

I. General theoretical framework

II. The complex nature of digital communication networks

III. Internet vs. physical geography: the role of distance

IV. An application: the digital accessibility of European cities

V. Concluding remarks future research

I. General framework

Background

- The new spatial form of the *space of flows* (Castells, 1996).
- Virtual geography: cyberplace vs cyberspace (Batty, 1997).
- Internet geography or cybergeography.
- The Internet is *not* a homogenous system equally spread around places (Gorman and Malecki, 2000).
- The placeless *cyberspace* depends on real world's fixities (Kitchin, 1998a and 1998b) found on *cyberplace*, which is the infrastructural reflection of the cyberspace on the physical space (Batty, 1997).
- More than one Internet geography (Zook, 2006).

I. General framework

The urban economic geography of the Internet infrastructure

- **Urban geography**: The internet is mostly an urban phenomenon (Rutherford et al., 2004).

- **Economic geography**: ICTs are the backbone of the new – digital – economy (Antonelli, 2003), with processes of production, distribution and exchange increasingly reliant on them.

Studies on the urban economic geography of the Internet infrastructure

Study	Region	Spatial unit	Indicator	Time
Wheeler and O'Kelly 1999	USA	city, backbone networks	Tc	1997
Gorman and Malecki 2000	USA	city	tc, tb, network distance	1998
Moss and Townsend 2000	USA	city	Tb	1997-1999
Malecki and Gorman 2001	USA	city	tc, tb number of hops	1998
Townsend 2001a	World	city	Tb	2000
Townsend 2001b	USA	city	tc, tb, domains	1997, 1999
Malecki 2002a	Europe	city	tc, tb, colocation points	2000
	Europe, Asia, Africa, Americas	continent	peering points	2000
	USA	city	tc, tb, b colocation points	1997-2000
O'Kelly and Grubesic 2002	USA	backbone networks, city	c, tc	1997-2000
Gorman and Kulkarni 2004	USA	city	tb,tc, c	1997-2000
Malecki 2004	USA	city	tb, b	1997-2000
Rutherford et al. 2004	Europe	city	b, tb, tc	2001
Schintler et al. 2004	Europe, USA	city	Tc	2001, 2003
Rutherford et al. 2005	Europe	city	c, tc, tb	2001, 2003
Devriendt et al 2008	Europe	city	intercity links, IXPs	2001, 2006
Devriendt et al 2010	Europe	city	intercity links, IXPs	2008
Rutherford forthcoming	Europe	city	c, tc, tb	2001, 2004
Tranos and Gillespie 2008	Europe	city	tb, tc	2001
Tranos forthcoming	Europe	city	c, b, tc, tb	2001-2006
Malecki and Wei 2009	World	country, city	tc, tb	1979-2005

b = bandwidth, c = connectivity (i.e. number of connections), t = total; *(Tranos and Gillespie 2011)*

I. General framework

Global city process

“The global city is not a place but a process. A process by which centres of production and consumption of advanced services, and their ancillary local societies, are connected in a global network, while simultaneously downplaying the linkages with their hinterlands, on the basis of informational flows‟ (Castells 1996, 417).

The Internet support the globalization process, as it is responsible for the transportation of the weightless goods of the global digital economy, but also for the transportation of the ideas which underpin this global process (Taylor, 2004; Graham and Marvin, 2001; Rimmer 1998; Cieslik and Kaniewska, 2004)

ICTs enabled the spatial dispersion of economic activity *(long distance management)* and reorganisation of the finance industry *(instant financial transactions)* (Sassen, 1991).

I. General framework

What is the impact of physical distance on digital communications?

- **Is it the end of distance**? While we haven't experience the *death of cities* (Gilder, 1995; Drucker 1989 cited in Kolko, 1999), *the death of distance* (Cairncross, 1997), *the emergence of electronic cottages* (Toffler, 1981) and in general to *the end of geography* due to ICTs, we still do not know how distance affects virtual interaction? Does physical space perform a complementary or a supplementary role in digital communications?

- Test whether Tobler‵s (1970, 236) first law of geography is valid in the frame of the digital economy.

  "Everything is related to everything else, but near things are more related than distant things".

I. General framework

How de we approach this question?

1. Explore the complex nature of digital communication networks

2. Empirically test the impact of physical distance using gravity models

3. Application of the above and introduction of the DA measure

II. The complex nature of digital communication networks

- The *new science of networks* (Barabási, 2002; Buchanan, 2002; Watts 2003, 2004)
- Large-scale real world networks and their universal, structural and statistical properties
- Better understanding of the underlying mechanisms governing the emergence of these properties (Newman, 2003)

II. The complex nature of digital communication networks

- Regional science and spatial economics have traditionally an interest on networks and interregional systems (Cornell University, 2011).
- Reggiani (2009) explores in detail the joint between spatial economics and network analysis:

Table 19.1 Dual analysis

Spatial economic analysis	Network analysis
Spatial structure	Topological structure
Statistical distribution of city population (Rank-size rule)	Statistical distribution of nodes (with k links)
Rank-size coefficient (minus or greater than 1)	Power law coefficient (minus or greater than 2)
Homogeneity vs. Heterogeneity	Homogeneity vs. Heterogeneity

Table 19.3 Synthesis scenario: two sides of the same coin

Spatial Economic analysis	Network analysis
(Complex) interactions between nodes	(Complex) interactions between nodes
Focus on the related economic variables	Focus on the related links
Focus on the economic meaning of the functional forms	Focus on the connectivity patterns of the functional forms

II. The complex nature of digital communication networks

Two main streams of complex network analysis:

- A more **descriptive** one, which focuses on various network measures and compares real networks with theoretical models such as *scale-free* networks, mostly using the (cumulative) degree distribution (e.g. Gorman and Kulkarni 2004; Schintler et al 2004; Regianni et al 2010; Tranos 2011)

- A **hard modeling** one, which is based on modeling exercises in order to simulate the evolution of empirical networks. Based on *stochastic* approaches and *statistical physics* (e.g. Barabási and Albert 1999; Albert and Barabási 2002)

II. The complex nature of digital communication networks

- Examples of such complex networks include: *transport* and ***telecommunication*** *flows* and their underpinning ***infrastructural*** *networks, trade, migration* etc.

- *Spatial Complex Networks*: physical, digital, virtual, economic, logical, social and other type of networks . These are “systems composed of a large amount of elementary components [i.e. links and nodes] that mutually interact through non-linear interactions, so that the overall behaviour is not a simple combination of the behaviour of the elementary components” (Crucitti et al 2003).

II. The complex nature of digital communication networks

Structural comparison of two digital networks:

- physical Internet backbone network
- virtual IP (Internet Protocol) network

City-to-city networks aggregated at NUTS3 level

Represent both **supply** (physical infrastructure) and **demand** (IP links) for city-to-city digital communications

Observations over time (2005-2008)

data sources: Telegeography 2009 and DIMES Project 2012

II. The complex nature of digital communication networks

Network measures

		nodes	edges	av. dist.	*av. dist. RN*	diam.	*diam. RN*	CC	*CC RN*
IP	**2005**	1324	19881	2.384	*2.471*	5	*4*	0.683	*0.024*
	2008	1186	18647	2.199	*2.359*	5	*3*	0.673	*0.027*
IB	**2005**	72	215	2.477	*2.57*	5	*5*	0.563	*0.086*
	2008	87	240	2.684	*2.807*	6	*5*	0.529	*0.092*

- Av. distance < Av. distance RN
- CC > CC RN

➔ Small world characteristics

II. The complex nature of digital communication networks

Power and exponential law fits (OLS)

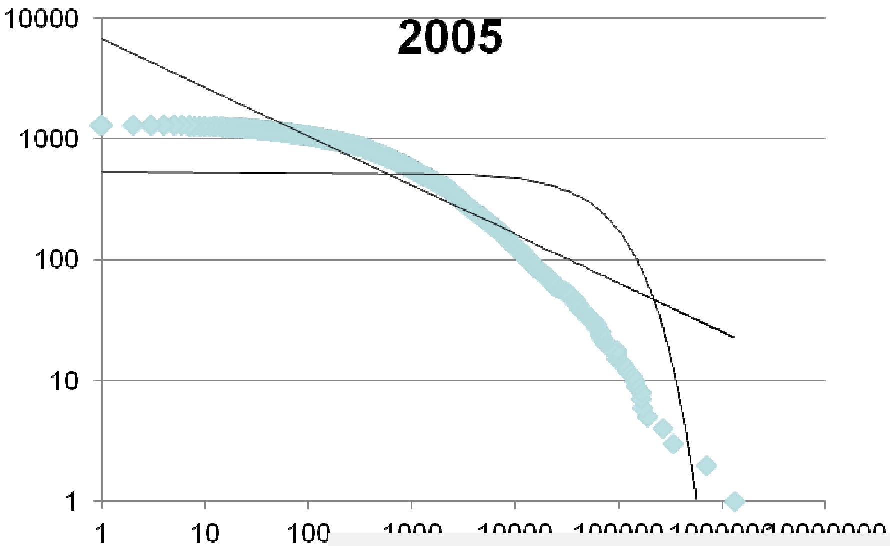
		Exponential		Power	
		R^2	**Coef.**	**R^2**	**Coef.**
IP	2005	0.26	1.E-05	**0.8**	-0.405
	2008	0.21	8E-06	**0.79**	-0.4
IB	2005	0.8	5.00E-06	0.84	-0.332
	2008	0.74	2.00E-06	0.78	-0.3

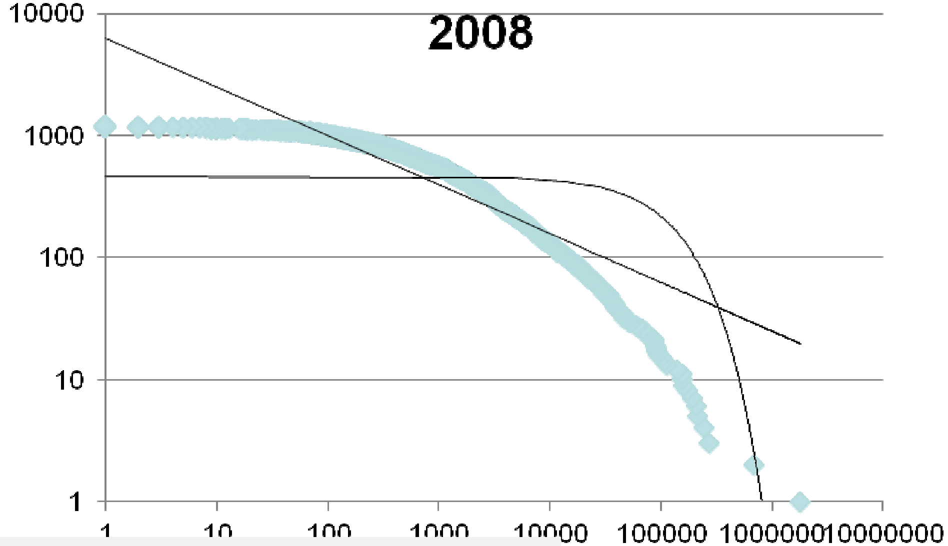
Power laws clearly fit better to IP networks ➔ *scale free* networks
Ambiguity for IB networks ➔ fail to form a clear *power law distribution*

Distinctive points:

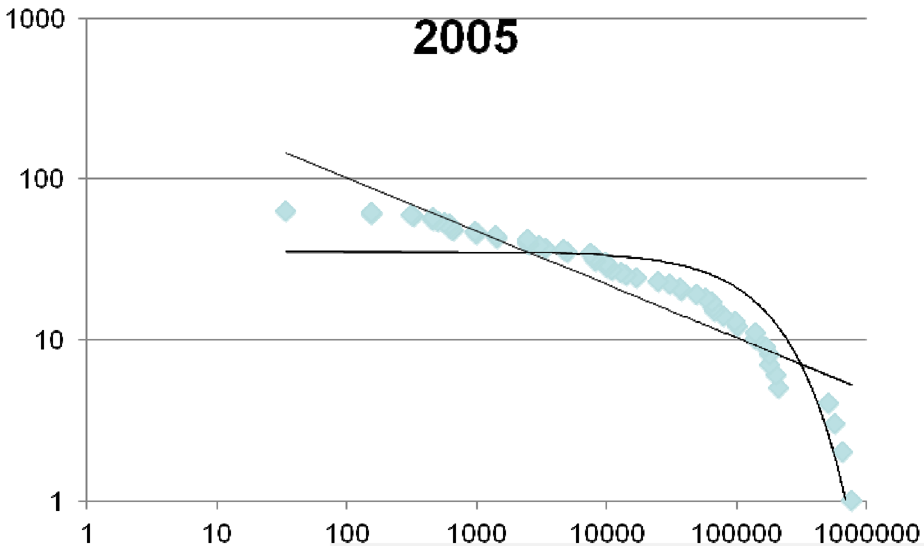
- More *heterogeneous* IP networks vs. more *homogeneous* IB networks
- The *physical constraints*, which are important even for the development of the digital Internet infrastructure, but are absent from the virtual IP networks

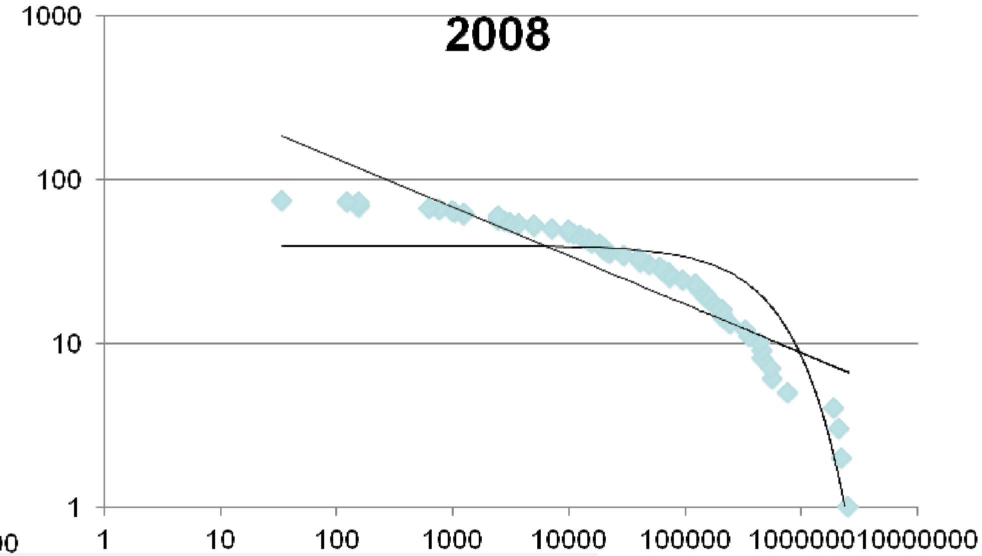
II. The complex nature of digital communication networks





Cumulative degree distribution for IP networks





Cumulative degree distribution for IBN networks

III. Internet vs. physical geography: the role of distance

Empirical testing

Gravity model to test the impact of physical distance on city-to-city IP communications links aggregated at NUTS3 city-region level.

$$\ln(IP_{ij,t}) = \alpha_0 + \alpha_1 \ln(O_{i,t}) + \alpha_2 \ln(D_{j,t}) + \beta_0 * t + \beta_1 \ln(dist_{ij}) + \beta_2 * t \ln(dist_{ij}) + \beta_3 * t^2 \ln(dist_{ij}) + \beta_4 * cntr_{ij} + \varepsilon_{ij,t}$$

$IP_{ij,t}$: the intensity of IP links between i and j

$O_{i,t}$ and $D_{j,t}$: a set of variables indicating the mass of i and j: GDP and population

t: time trend

$dist_{ij}$: physical distance between i,j

$cntr_{i,j}$: a binary variable indicating that i,j are located in the same country

Panel data specification: c. 40k city-to-city links for 4 years

III. Internet vs. physical geography: the role of distance

Random Effects

Distance has

negative impact on

IP communications

Dependent: ip_ln	(1)	(2)	(3)
dist_ln	-0.372	-0.383	-0.365
	(0.012)***	(0.011)***	(0.012)***
cntr	0.663	0.571	0.613
	(0.026)***	(0.025)***	(0.027)***
t_	-0.035	-0.019	-0.022
	(0.005)***	(0.006)***	(0.006)***
gdp_o_ln	0.316		0.194
	(0.009)***		(0.022)***
gdp_d_ln	0.205		0.242
	(0.008)***		(0.023)***
pop_o_ln		0.329	0.157
		(0.010)***	(0.026)***
pop_d_ln		0.208	-0.044
		(0.009)***	(0.028)
Constant	-0.421	1.292	-0.343
	(0.144)***	(0.112)***	(0.157)**
R-square	0.1225	0.1061	0.11
Observations	71445	72874	66516
Number of groups	37263	39551	35623

Standard errors in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%

III. Internet vs. physical geography: the role of distance

Hausman and Taylor (1981) IV

Distance has

negative impact on

IP communications

Dependent: ip_ln		(1)	(2)	(3)
Time invariant exogenous	dist_ln	-0.067	-0.185	-0.635
		-0.061	(0.067)***	(0.079)***
Time variant exogenous	cntr	3.139	2.96	2.699
		(0.082)***	(0.082)***	(0.088)***
	t_	-0.2	-0.034	-0.153
		(0.010)***	(0.008)***	(0.019)***
Time variant endogenous	gdp_o_ln	2.348		1.456
		(0.056)***		(0.196)***
	gdp_d_ln	2.25		1.447
		(0.056)***		(0.195)***
	pop_o_ln		2.89	1.753
			(0.080)***	(0.216)***
	pop_d_ln		2.769	1.639
			(0.080)***	(0.217)***
Constant		-41.413	-32.312	-42.498
		(0.807)***	(0.717)***	(1.378)***
Observations		71445	72874	66516
Number of groups		37263	39551	35623

Standard errors in parentheses

* significant at 10%; ** significant at 5%; *** significant at 1%

III. Internet vs. physical geography: the role of distance

Empirical testing

Gravity model to test the impact of physical distance on city-to-city IP Internet backbone links (physical infrastructure) aggregated at NUTS3 city-region level.

$$\ln(IB_{ij,t}) = \alpha_0 + \alpha_1 \ln(O_{i,t}) + \alpha_2 \ln(D_{j,t}) + \beta_0 * t + \beta_1 \ln(dist_{ij}) + \beta_2 * t\ln(dist_{ij}) + \beta_3 * t^2 \ln(dist_{ij}) + \beta_4 * cntr_{ij} + \varepsilon_{ij,t}$$

$IB_{ij,t}$: the capacity of the international intercity Internet backbone links between i and j

$O_{i,t}$ and $D_{j,t}$: a set of variables indicating the mass of i and j: GDP and population

t: time trend

$dist_{ij}$: physical distance between i,j

Panel data specification: c. 260 city-to-city links for 4 years

III. Internet vs. physical geography: the role of distance

Random Effects

Distance appears to have *negative impact* on *digital infrastructure links…*

Dependent: tele_ln	(1)	(2)	(3)
dist_ln	-0.847	-0.672	-0.897
	(0.162)***	(0.164)***	(0.160)***
t_	0.292	0.328	0.247
	(0.031)***	(0.027)***	(0.035)***
gdp_o_ln	0.679		1.392
	(0.166)***		(0.272)***
gdp_d_ln	1.238		1.238
	(0.149)***		(0.263)***
pop_o_ln		0.193	-0.956
		(0.171)	(0.289)***
pop_d_ln		1.197	0.048
		(0.208)***	(0.368)
Constant	-7.928	1.578	-8.705
	(2.216)***	(1.919)	(2.206)***
R-square	0.3315	0.1667	0.3712
Observations	682	751	645
Number of groups	228	259	227

Standard errors in parentheses

* significant at 10%; ** significant at 5%; *** significant at 1%

III. Internet vs. physical geography: the role of distance

Hausman and Taylor (1981) IV

… but this is not

consistent

Dependent: tele_ln		(1)	(2)	(3)
Time invariant exogenous	dist_ln	-0.319	3.769	5.056
		(0.443)	(2.265)*	(2.916)*
Time variant exogenous	t_	0.364	0.448	0.596
		(0.051)***	(0.060)***	(0.102)***
Time variant endogenous	gdp_o_ln	-0.451		-1.205
		(0.852)		(0.956)
	gdp_d_ln	0.893		-0.925
		(0.622)		(0.843)
	pop_o_ln		-16.887	-19.51
			(5.056)***	(5.944)***
	pop_d_ln		1.669	3.793
			(4.757)	(5.708)
Constant		4.279	89.767	107.749
		(7.933)	(41.483)**	(51.504)**
Observations		682	751	645
Number of groups		228	259	227

Standard errors in parentheses

* significant at 10%; ** significant at 5%; *** significant at 1%

III. Internet vs. physical geography: the role of distance

Results

- Physical distance plays a significant negative role in the formation of cyberspace
- First results confirm that Tobbler's first law of geography applies in the cyberspace
- However, the role of distance is not as straightforward in the formation of the digital infrastructure due to topological constraints, which are found in the real – physical – world geographies
- ➔ Digital space is based on real world fixities

IV. An application: the digital accessibility of European cities

Rationale for a DA measure*

A well established parallel exists in the literature between transportation and ICT networks:

•while transportation infrastructure reduces transaction costs in trade, telecommunications infrastructure lowers transaction costs of trading ideas (Cieslik and Kaniewska, 2004)

•Telecommunications just like transportation are friction reducing technologies, because of their ability to reduce the cost of distance (Cohen et al., 2002, Cohen-Blankshtain and Nijkamp, 2004).

•"Similar to the transportation networks of the past two centuries (rail, road, air, water), the Internet transports the valuable weightless goods of the digital economy: information, knowledge and communication" (O'Kelly and Grubesic 2002, 537).

**in collaboration with Aura Reggiani*

IV. An application: the digital accessibility of European cities

Rationale for a DA measure

- From the technical point of view, the Internet is not a unique system evenly scattered, regardless of core or periphery (Gorman and Malecki, 2000).
- Geographic location affects Internet connectivity and the speed at which data can be transmitted and received due to the uneven spatial allocation of the Internet's physical infrastructure (Malecki and Moriset, 2008).
- The concentration of digital infrastructure in specific locations may influence the economic development as it can provide better access to the digital economy, affecting the competitiveness at micro and macro level: Internet and effectiveness effects ➔ cost reduction and revenue increase for corporations; Internet connectivity effects and the endowment of location factors ➔ the accessibility and the attractiveness of territories (Camagni and Capello, 2005).
- E.g. Internet infrastructure can both result in attracting new firms which can exploit such infrastructure and increase the productivity of the existing firms (Cornford and Gillespie, 1993). Additionally, such infrastructure might also result in higher quality digital services for end users.

IV. An application: the digital accessibility of European cities

Rationale for a DA measure

Topological similarities exist between transport and telecommunications:

The parallel between the Internet physical infrastructure and the road infrastructure

Importance at	The Internet infrastructure		Road infrastructure
Inter-city level	Backbone networks	↔	Motorways
	IXPs / private peering points	↔	Interchanges
Intra-city level	POPs	↔	Access nodes
	MANs / local loops	↔	Intra-city road networks
	IP addresses	↔	Premises

IV. An application: the digital accessibility of European cities

Definition of DA

Starting point: Hansen's (1959) seminal work on potential accessibility

DA: the potential for virtual interactions in the digital space (i.e. digital communications)

$$DA_i = \sum_j CP_j f(d_{ij})$$

- *CPj* (cyber-place) denotes the capacity of the installed digital infrastructure in region *j*
  - International intercity Internet backbone capacity (Telegeography, 2009).
  - Highest tier of the Internet physical infrastructure / responsible for the Internet's global character as it connects remote destinations (Malecki, 2004)
  - The installed capacity due to Internet backbone networks reflects the potential of the city to *attract, generate or route IP data flows*.
- $f(d_{ij})$ denotes the impedance function

IV. An application: the digital accessibility of European cities

Definition of DA

$$DA_i = \sum_j CP_j f(d_{ij})$$

- $f(d_{ij})$ denotes the impedance function based on physical distance *i,j*
- This follows Pastor-Satorras and Vespignani (2004, p. 99) who highlight that
  "connection cost increases with distance and eventually imposes a preference for a nearby, medium-sized hub, instead of the largest one that could be located far away in geographical distance"
- In addition, the first Internet topology generator, which was produced by Waxman (1988) and was extensively used for protocol testing, incorporated the negative impact of physical distance between any two nodes.
- Based on the above, we would expect that physical distance would have a negative effect in the digital accessibility of a place.

IV. An application: the digital accessibility of European cities

Definition of DA

$$DA_i = \sum_j CP_j f(d_{ij})$$

We test three different impedance functions:

$$f(d_{ij}) = e^{-\beta_1 d_{ij}}$$

$$f(d_{ij}) = d_{ij}^{-\beta_2}$$

$$f(d_{ij}) = e^{-\beta_3 (\ln d_{ij})^2}$$

using a simple unconstrained SIM

$$CP_{ij} = kCP_i CP_j F(d_{ij})$$

IV. An application: the digital accessibility of European cities

Calibration

Table 1: OLS results for *f(d)* estimation using SIM

year	f(d)	b	R^2	t	N
2005	Exponential	-0.002	0.292	-8.86***	192
		-0.002	0.28	-8.48***	187
	power	-1.915	0.402	-11.31***	192
		-1.653	0.321	-9.36***	187
	log-normal	-0.150	0.393	-11.08***	192
		-0.127	0.325	-9.43***	187
2008	Exponential	-0.002	0.267	-8.68***	209
		-0.002	0.264	-8.50***	204
	power	-1,523	0.277	-8.92***	209
		-1,376	0.238	-7.94***	204
	log-normal	-0.123	0.284	-9.08***	209
		-0.11	0.252	-8.24***	204

➔ no obvious function that explains better the impact of distance on the capacity of the digital infrastructure.

➔ calculate the DA measure for all the three different impedance function specifications.

DA Results

- power and log-normal functions are almost identical (Pearson correlation = 0.98)
- exponential and power are the most different, but still highly correlated (0.7)
- Comparison with topological measure (Tranos 2011) ➔ Although physical networks, IBN are dynamic as the correlation with the degree distribution changes over time (higher Pearson correlation for exponential in 2005 and log-normal for 2008).
- Overtime, log-normal appears to fit better with the degree distribution

DA measures

	2008			2005		
	exp.	power	log-norm.	exp.	power	log-norm.
Paris	*3*	*1*	*2*	*2*	*1*	*2*
London	*1*	*2*	*1*	*1*	*2*	*1*
Frankfurt	*2*	*3*	*3*	*3*	*3*	*3*
Amsterdam	*5*	*4*	*4*	*4*	*6*	*4*
Düsseldorf	*19*	*5*	*5*	*16*	*9*	*10*
Copenhagen	*22*	*6*	*6*	*5*	*4*	*5*
Brussels	*24*	*7*	*9*	*10*	*5*	*6*
Wien	*17*	*8*	*8*	*11*	*8*	*8*
Milan	*6*	*9*	*7*	*8*	*15*	*11*
Hamburg	*20*	*10*	*10*	*7*	*10*	*9*
Geneva	*4*	*11*	*11*	*12*	*7*	*7*
Prague	*18*	*12*	*12*	*17*	*13*	*14*
Oslo	*32*	*13*	*15*	*15*	*14*	*13*
Warsaw	*33*	*14*	*17*	*14*	*12*	*12*
Budapest	*39*	*15*	*21*	*20*	*17*	*17*
Basel	*37*	*16*	*34*	*35*	*11*	*20*
Nuremberg	*10*	*17*	*13*	*60*	*45*	*51*
Bucharest	*47*	*18*	*29*	*38*	*25*	*30*
Zürich	*21*	*19*	*19*	*13*	*18*	*15*
Stockholm	*12*	*20*	*14*	*6*	*23*	*18*
Munich	*45*	*21*	*31*	*24*	*19*	*21*
Dublin	*36*	*22*	*25*	*19*	*20*	*19*
Madrid	*15*	*23*	*18*	*9*	*22*	*16*
Lisbon	*25*	*24*	*24*	*25*	*26*	*27*
Stuttgart	*55*	*25*	*36*	*32*	*21*	*24*
Monaco	*7*	*26*	*16*	*56*	*56*	*57*
Berlin	*42*	*27*	*28*	*50*	*46*	*47*
Marseille	*8*	*28*	*20*	*31*	*36*	*35*

DA Results

- The golden diamond of the Internet infrastructure in Europe
- Changes over time – urban dynamics
- Regional hub cities of Central and Eastern Europe
- The rather low DA of gateway cities to other continents
- The strong presence of German cities reflecting the polycentric urban development pattern (Munich and Stuttgart are just below)

DA based on log-normal

	2008	2005
London	*1*	*1*
Paris	*2*	*2*
Frankfurt	*3*	*3*
Amsterdam	*4*	*4*
Düsseldorf	*5*	*10*
Copenhagen	*6*	*5*
Milan	*7*	*11*
Wien	*8*	*8*
Brussels	*9*	*6*
Hamburg	*10*	*9*
Geneva	*11*	*7*
Prague	*12*	*14*
Nuremberg	*13*	*51*
Stockholm	*14*	*18*
Oslo	*15*	*13*
Monaco	*16*	*57*
Warsaw	*17*	*12*
Madrid	*18*	*16*
Zürich	*19*	*15*
Marseille	*20*	*35*
Budapest	*21*	*17*
Turin	*22*	*62*
Brno	*23*	*37*
Lisbon	*24*	*27*
Dublin	*25*	*19*
Berlin	*28*	*47*
Bucharest	*29*	*30*

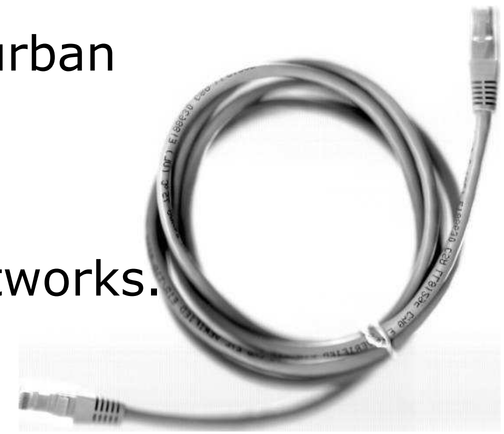
IV. An application: the digital accessibility of European cities

Discussion

- We proposed here a new measure indicating the potential for virtual interaction
- It is an infrastructural approach, which highlights the importance of the inclusion of the digital infrastructure in the regional development agenda
- We tested via this *application* the role of distance in the digital domain
- A new urban hierarchy based of the cyberplace.
- Not only another urban hierarchy. As we proved elsewhere (Tranos forthcoming) digital infrastructure has an impact on regional economic development.

V. Concluding remarks future research

- Tobler’s law applies in virtual communications, but real-world topological constraints prevent its application in cyberplace.
- Empirically confirm that cyberspace is based on real world fixities reflected on distance.
- Feed the discussion in the literature on the role of proximity with empirical results.
- Identify the impact of physical constraints in preventing IBN from shaping SF networks. At the same time, the lack of such constraints enables IP to form SF networks.
- Introduce a new measure of DA utilising the above distance effects. Need to further explore the impact of DA on urban development trajectories.
- Explore the role of different proximities.
- Model the urban dynamics observed due to digital networks.
- Model the evolution of these networks.



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