The Economic Impact of Broadband on Growth: A simultaneous approach[*]

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This paper investigates how broadband penetration affects economic growth. A macroeconomic production function with a micromodel for broadband investment is used to estimate the impact of broadband infrastructure and growth. The results indicate a significant causal positive link especially when a critical mass of infrastructure is present. The scope of this research is the 15 European Union countries based on data collected for the period 2003 – 2006.

INTRODUCTION

Explaining the determinants of economic growth ranks among the most active fields in economics. Fifty years ago economists considered technological change as the single most important parameter for growth and labor productivity (Abramovitz 1956, Kendrick 1956, Solow 1957). The models that were used to measure the technological effects on growth varied significantly from the endogenous approach - 'growth driven by technological change that arises from intentional investments of profit maximizing individuals' (Romer, 1990) to the earlier aggregate production functions with exogenous technological changes (Solow, 1957). A large number of papers have since then commented on these models (Fisher, 1969) and attempted to disentangle the determinants of growth (Mankiw et al, 1992; Barro, 1998; Barro and Salla-i-Martin, 2003). Perhaps the most convincing evidence in favor of the technological developments as a growth engine comes from Rosenberg (1972) providing a comprehensive survey of the afore-mentioned relationship for the American economy since the 1800s.

This paper attempts to measure the economic impact of the telecommunications infrastructure on growth and more specifically the effects of broadband infrastructure. The growing numbers of internet subscribers worldwide make this study particularly important. This issue has also received considerable regulatory and public policy attention especially in the developed countries. This paper uses evidence from 15 European Union countries over 4 years to estimate the impact of broadband infrastructure.

Investment in infrastructure affects growth and broadband infrastructure is no exception to this rule. Aschauer (1990), Munell (1992) and Gramlich (1994) focus on the effects of infrastructure and its relationship to growth and provide evidence for its existence. Broadband infrastructure investment can increase economic growth in various ways. More obviously the equipment, the drilling and the ductwork lead to increases in the demand of goods and services. This first level of infrastructural investment is nevertheless not as significant as the utility derived from the use of the network.

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Broadband networks provide the framework for the delivery of different services ranging from telephony and its variants (PSTN, VoIP and video phones) to high speed internet access and very diverse multimedia services (video streaming, online games, tele-working etc). Speed of connection guarantees the provision of wealthier information and decreases search and transaction times. As such this technology improves the capabilities of the labor force and the communication between firms. The use of this infrastructure spreads to other industries and contributes to their profits thus affecting their overall growth. While the telecommunications industry is primarily affected by the infrastructure itself the important spillovers of broadband networks result in externalities in the other sectors of the economy.

Measuring the returns of public infrastructure has received considerable attention and debate. The results of some early studies have often been found to suffer from simultaneity bias and spurious correlation[1]. More recent papers account for these issues either by incorporating first differences approach[2] or by moving to smaller data aggregation[3]. Munell (1992) supports that the 'legitimate' criticism to the public infrastructure debate should focus on reverse causation - thus implying that the direction of causation may run from output to infrastructure as well[4]. Clearly the same issues of reverse causality and spurious correlation could exist in the broadband infrastructure. This essentially translates into two different effects: a) the increase of economic growth due to increases in broadband infrastructure and its externalities and b) the increase in the demand of broadband services due to higher economic output. Thus it is vital to explicitly disentangle the effect of growth on the infrastructure in order to measure the intended effect. In this paper I estimate the effect of broadband infrastructure on growth using a simultaneous equations model. This model endogenizes broadband investment by incorporating broadband supply, demand and output equations. The system is then jointly estimated with a macro production function hence accounting for the simultaneity effects[5]. The model used in this paper is based on the telecommunications (telephony) infrastructure model used by Roeller and Waverman (2001).

Broadband networks share some common features with other public infrastructure investments. However the information intensity and the breadth of activities that can be supported by high level software applications – ranging from business critical processes to entertainment and e-learning – are some of their unique characteristics. Moreover some very important parameters regarding the deployment of these networks are their reach to thinly populated or rural areas and the level of participation that they attract. Where the state of the infrastructure is rudimentary

[1] See Aschauer (1989)

[2] Aaron (1990), Hulten and Schwab (1990), Jorgenson (1991), Tatom (1991)

[3] From country data to State and regional data the estimates of the output elasticity of public capital dwindles. Munell (1992) states that these changes are attributed to 'leakages' because '…one can not capture all of the payoff to an infrastructure investment by looking at a small geographic area'.

[4] Eberts and Fogarty (1987) examined the question of causality by looking at public and private investment data from 1904 to 1978 for 40 metropolitan areas. They found causation running in both directions. Their analysis indicated that public investment led private investment in cities that experienced most of their growth before the 1950s, while the reverse was true for southern cities and cities that grew faster since 1950.

[5] The time and country fixed effects that are applied control for the spurious correlation that arises from other non-broadband specific local investments. Other econometric controls, e.g. standard error clustering for heteroscedasticity and autocorrelation, are applied to the model as well. The standard error clustering estimates are first clustered by country, estimated in single equations and then put in the simultaneous equations model.

inter-firm communications are limited. Broadband networks – as with most networks – are also size dependent. Various models have been studied in terms of the value of a computer network relative to its size (Metcalfe, Reed, Odlyzco 2005) which unanimously find that there is at least[6] a proportional link between the two values. Thus, the inclusion of more subscribers increases the size of the network and the overall gains to its members. These gains might have an impact on productivity, education and social welfare[7]. From the firms' perspective a wider audience makes the platform more attractive for investments. These types of benefits are not existent in the transportation or the utilities networks and account for the externalities of broadband networks. The question behind this situation is whether there are actually certain specific network size-levels where these externalities appear. This would imply that once a critical mass of broadband penetration is achieved the relative returns to growth should rise in a more than expected trend.

The rest of the paper is organized as follows. First I describe some related studies and their findings. Then I present the model and the particular discussion for each equation. After that I present the data and some summary statistics. Finally I discuss the results and some future remarks about this area of research.

RELATED STUDIES

There has been a considerable amount of empirical work on the economic impact of telecommunications on growth. The methodologies that have been used vary on issues like data availability and different econometric specifications. The broad outcome of these studies concludes to a positive and significant link between telecommunications infrastructure and growth. The discussion below follows a chronological order of the relevant studies and focuses on their outcomes. Since telecommunications technology has undergone important changes in the last fifteen years the focus of the earlier studies in mainly on the telephony network.

An early study by Hardy (1980) used a group of 60 countries for the period 1960 to 1973 in order to measure the role of telephone on economic development. The regressions show a significant impact of tele-density (telephone lines per capita) on GDP per capita. However a separate estimation for developed and developing countries shows that the results are not significant. The existence of important fixed effects or the reverse causality might be possible explanations to these results (Roeller and Waverman, 2001).

Leff (1984) analyzes 'the welfare effects of investment in telecommunications facilities (primarily telephone) in developing countries' and used cross-section data on 47 developed and developing countries. The econometric results indicate that the relationship between telecommunications infrastructure and economic growth is positive and significant.

Cronin *et al* (1993) using time series analyses of 31 years of US data (1958-1988) find a statistically significant causal relationship between productivity growth

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[6] Metcalfe finds that the value of the network is proportional to the square of its size. Reed supports that its value grows exponentially to its size. There is also a more conservative view that the value grows proportionally to $n \log(n)$, where n is the number of people connected (Odlyzco, 2005).

[7] Productivity gains in terms of time saving and increased quality, education gains because of e-learning activities and social welfare gains due to the wide awareness and open dialogue for several issues. Forum participants discuss - asynchronously or real time - and learn about ecology, politics, medical advancements etc with any other user of the web.

and telecommunications. In this setting the level of US economic activity at any point in time is a 'reliable predictor of the amount of US telecommunications investment at a later point' in time and 'the amount of US telecommunications investment at any point in time is a reliable predictor of the level of US economic activity at a later point in time'.

Greenstein and Spiller (1995) study the impact of telecommunication infrastructure on a country's economic activity in two sectors: fire, insurance and real estate; and manufacturing. The framework used to measure the effect of the infrastructure on long run economic activity is a pooled cross-section time series equation and the dataset spreads from 1986-1992. The results indicate that modernization of the telephone network is associated with more fire, insurance and real estate activity in the local region, while it is not associated with more manufacturing. Once other determinants of growth are controlled for, a doubling of fiber optic cable leads to at least a 10%, and possibly a much higher, increase in the level of economic activity in fire, insurance and real estate.

Madden and Savage (1998) empirically examine the relationship between gross fixed investment, telecommunications infrastructure investment and economic growth for a sample of transitional economies in Central and Eastern Europe. In particular, they focus on empirically determining the direction of influence, and timing, between investment and growth. The finding that telecommunication investment, especially when measured by main telephone lines, is related to economic growth is a key outcome of the study. This result suggests that improving the chronic underinvestment in the telecommunications infrastructures of Central and Eastern European countries may ultimately improve the channel between aggregate investment and growth, economy-wide.

Savage (2000) points to the absence of investment data for many developing countries and questions the practice of using main telephone lines to measure the stock of telecommunications capital since the accuracy of this proxy has not been subject to careful statistical scrutiny. Savage (2000) develops a supply-side growth model which employs tele-density and the share of telecommunications investment in national income as telecommunications capital proxies. The results suggest 'a significant positive cross-country relationship between telecommunications capital and economic growth, when using alternative measures of telecommunications capital'.

A more recent study by Roller and Waverman (2001), jointly estimates a micromodel for telecommunications investment with a macro production function for the OECD group of countries for the period 1970-1990. They find a strong causal relationship between telecommunications infrastructure and productivity, and additionally they indicate that this occurs only when telecommunications services reach a certain threshold, which is near universal levels. An adaptation of the model used by Roeller and Waverman is used in this study while the focus is broadband infrastructure rather than telephone network.

Seetharam and Sridhar (2004) investigate the simultaneous relationship between telecommunications and the economic growth, using data for developing countries. Using 3SLS they estimate a system of equations that endogenizes economic growth and telecom penetration along with supply of telecom investment and growth in telecom penetration. They find that there is a significant impact of cellular services on national output, when controlling for the effects of capital and labor. The impact of telecom penetration on total output is found to be significantly lower for developing countries than the reported figure for OECD countries, dispelling the convergence hypothesis.

Datta and Agarwal (2004) empirically investigate the role of telecommunication infrastructure on long run economic growth for a sample of 22 OECD countries. Using panel data and a dynamic fixed effects method for estimation they account for omitted variable bias of single cross-section regression. The results show that telecommunications is both statistically significant and positively correlated with growth in real GDP per capita growth for these countries. The results are robust even after controlling for investment, government consumption, population growth, openness, past levels of GDP, and lagged growth. The results further indicate that the telecommunications investment is subject to diminishing returns, suggesting thereby that countries at an earlier stage of development are likely to gain the most from investing in telecom infrastructure.

Lehr, Osorio, Gillett, Sirbu (2006) present a first attempt to measure broadband's impact by applying controlled econometric techniques to national-scale data. After controlling for community-level factors that affect broadband availability and economic outcomes (income, education, and urban vs. rural character) the results show that broadband access enhances economic growth and performance, and that the economic impact of broadband is real and measurable. In particular they find that for the period 1998-2002 communities in which mass-market broadband became available by December 1999 experienced more rapid growth in employment, the number of businesses overall and businesses in IT-intensive sectors. They don't find statistically significant impact on wages but the higher market rents imply an impact on property values.

Duggal, Saltzman, Klein (2006) incorporate both public and private infrastructure within the framework of a nonlinear production function. Their model specifies a technological growth rate as a nonlinear function of government infrastructure and private infrastructure generated by the information sector of the economy—cable, wireless stations, satellites, internet facilities, broadcasting, etc. The empirical estimates generated by the model imply increasing returns to scale for the US economy in the last few years. The evaluation of the growth accounting equation implies that information technology was the largest contributing component to growth during the expansion of the 1990s.

ECONOMETRIC MODEL

As mentioned previously the approach used here is a structural econometric model within a production function framework that endogenizes telecommunications investment. The reason for using this type of model is the following. The effect we are trying to capture is a two-way relationship between growth and broadband infrastructure. While we do expect wealthier people to have higher demand for goods and services we want to estimate how much the country's growth might be affected by their use of the broadband networks. In order to illustrate this causal link between the two variables we use this model that explicitly disentangles the values in a simultaneous equations model. Therefore a micro model of supply and demand is specified and jointly estimated with the macro production equation. This way while endogenizing for the investment we can control for the causal effects of this two-way relationship.

The national aggregate economic output (GDP) is used in the production function and is related to the stock of capital net of telecommunications capital (K), the stock of human capital (HK), the stock of broadband infrastructure (BROADBAND) and the education level of the labor force (EDU). The stock of broadband infrastructure is needed rather than the broadband investment because consumers demand infrastructure and not investment per se. The model used here is based on the Roeller and Waverman (2001) simultaneous equations model. The aggregate production function is as follows:

$$GDP_{it} = f(K_{it}, HK_{it}, BROADBAND_{it}, EDU_{it})$$

There is a wide literature supporting the strong relationship between stock of capital and labor force in a country with the GDP. The variable for capital used here is split between telecommunications capital $BROADBAND_{it}$ and all other capital HK_{it}. The telecommunications capital for the EU15 countries is measured by their broadband infrastructure and not by their fixed telephony infrastructure. The reason for that is that the whole region has higher than 100% penetration in fixed telephony thus indicating that the copper legacy infrastructure is of the same level across the region[8]. The broadband infrastructure demands other investments on top of the legacy networks. These investments are taken into account by the broadband penetration level in each country. The education variable included in the equation is also linked with productivity and growth and affects the quality of the labor force in a country.

In order to differentiate between the effect of BROADBAND on GDP and the inverse we specify the following micro model.

Demand for broadband infrastructure:

$$BROADBAND_{it} = h(GDPC_{it}, BBPr_{it}, EDU_{it}, URB_{it}, RND_{it})$$

The demand equation states that broadband penetration is a function of GDP per capita, the price of a standard service for the connection to the network, the percentage of the population that is educated above a certain level (high school and university), the percentage of the population that lives in densely populated areas and the aggregate amount spent on research and development.

Supply of broadband infrastructure:

$$BBI_{it} = g(GD_{it}, BBPr_{it})$$

The supply equation links the aggregate broadband investment in a country to the annual surplus (or deficit) as a percentage of the GDP and broadband price levels for that period. The reason for the link between the countries' deficit and broadband investment is that the deficit exogenously affects public and private investment.

[8] All EU15 countries have higher than 40 main telephone lines per 100 inhabitants indicating that all homes are served by the fixed telephony network (2.5 people living in each house) – ITU statistics 2006

Higher deficit attracts more investment because of higher returns and lower risk[9]. (C. L. Mann, 2002)

Broadband infrastructure production function:

$$BROADBAND_{i,t} - BROADBAND_{i,t-1} = k(BBI_{it})$$

The infrastructure equation states that the annual change in broadband penetration is a function of the capital invested in a country during one year. It is important to understand that the difference in penetration levels is a function of the infrastructural change that is already used and utilized by the citizens of a country. There might be other parts of the invested capital – part of the BBI variable – that have not yet been realized and used by the people.

These three equations endogenize Broadband Infrastructure because they involve the supply and demand of broadband infrastructure. A detailed version of the model follows below:

Aggregate Production equation:

$$\log(GDP_{it}) = a_0 + a_1\log(K_{it}) + a_2\log(LF_{it}) + a_3\log(PEN_{it}) + a_4\log(EDU_{it}) + \varepsilon_{it}^{1} \quad (1)$$

Demand equation:

$$\log(PEN_{it}) = b_0 + b_1\log(GDPC_{it}) + b_2\log(BBPr_{it}) + b_3\log(EDU_{it}) + b_4\log(URB_{it}) + b_5\log(RND_{it}) + \varepsilon_{it}^{2} \quad (2)$$

Supply equation:

$$\log(BBI_{it}) = c_0 + c_1\log(GD_{it}) + c_2\log(BBPr_{it}) + \varepsilon_{it}^{3} \quad (3)$$

Broadband infrastructure production equation:

$$\log\left(\frac{PEN_{it}}{PEN_{i,t-1}}\right) = d_0 + d_1\log(BBI_{it}) + \varepsilon_{it}^{4} \quad (4)$$

Data and Correlations

The aim of this part is to investigate and identify certain relationships between the data for the telecommunications investment – or more specifically the broadband

[9] "A current account deficit can mean that a country is 'living beyond its means' because overall consumption and investment exceed the national savings of the economy. Alternatively, it can mean that a country is an 'oasis of prosperity' attracting investment from around the globe because the economy delivers higher investment returns at lower risk than other investment choices."

investment and the economic output. The dataset used for this study uses annual data from 15 European Union countries for the four-year-period between 2003 – 2006. The countries used are listed in Table I.

Table I

European countries used in the dataset

Austria	Italy
Belgium	Luxembourg
Denmark	Netherlands
Finland	Portugal
France	Spain
Germany	Sweden
Greece	United Kingdom
Ireland	

The data used have been collected by various sources depending on their nature and availability. Eurostat online resources were used to obtain information related to GDP, GDPC, Broadband penetration levels in 100 of population, labor force – population with full or part time work aged 15-64 – and government surplus or deficit as percentage of GDP. The Groeningen Growth Accounting Database was used to obtain information about the non residential capital stock net of telecommunications investment and the total telecommunications investment. A combination of data from OECD statistics and International Telecommunications Unions statistics were used to construct the variable of the Broadband price which utilized a level of constant speed at flat rate contract to obtain an unbiased benchmark of the price levels. For the demographics of the dataset, i.e. the urbanization variable (people living in areas with more than 500 inhabitants per sq kilometer per 100 population) the Population Division of the World Urbanization Project from the United Nations Department of Economic and Social Affairs provided the data. OECD statistics were used to obtain penetration levels - population with a broadband connection per 100 population. Finally the European Innovation Scoreboard Database (2006 version) provided the source for the education and research and development levels in each country in the dataset. Table II contains the variables used in the model. The subscripts i and t correspond to country and time values respectively.

Table II

Variables used in the model and descriptions

GDP_{it}	GDP in millions of euros	Eurostat statistics
$GDPC_{it}$	GDPC in euros	Eurostat statistics
K_{it}	Non-residential stock of telecommunications investment in millions of euros	GGDC growth accounting statistics
PEN_{it}	Level of broadband penetration in 100 inhabitants	OECD and Eurostat statistics
$BBPr_{it}$	Price of 1 Mbytes per second of flat rate internet connection (no data or time caps)	ITU statistics, OECD statistics

URB_{it}	People living in areas with more than 500 inhabitants per sq kilometer per 100 population	United Nations, Department of Economic and Social Affairs, Population Division (2006). World Urbanization Prospects
EDU_{it}	Population with tertiary education per 100 population aged 25-64	European Innovation Scoreboard 2006 Database
RD_{it}	Level of Public and Private investment in Research and Development in millions of Euros	European Innovation Scoreboard 2006 Database
BBI_{it}	Stock of telecommunications investment in millions euros	GGDC growth accounting statistics
LF_{it}	Population with full or part time work aged 15-64 in millions	Eurostat statistics
GD_{it}	Government surplus (+) or deficit (-) as percentage of the GDP	Eurostat statistics

More information about the data is included in the appendix. Before turning to the results there are some important correlations in the dataset. From these we will focus on the correlation between broadband penetration level and GDPC for the EU countries for the year 2006. As we can see in Figure 1 there is a clear trend followed by the participating countries. This graph is intended to enrich the understanding about the causal link that we need to describe. While Luxemburg is an obvious outlier in the graph the rest of the countries seem to be closely scattered around the trend line.

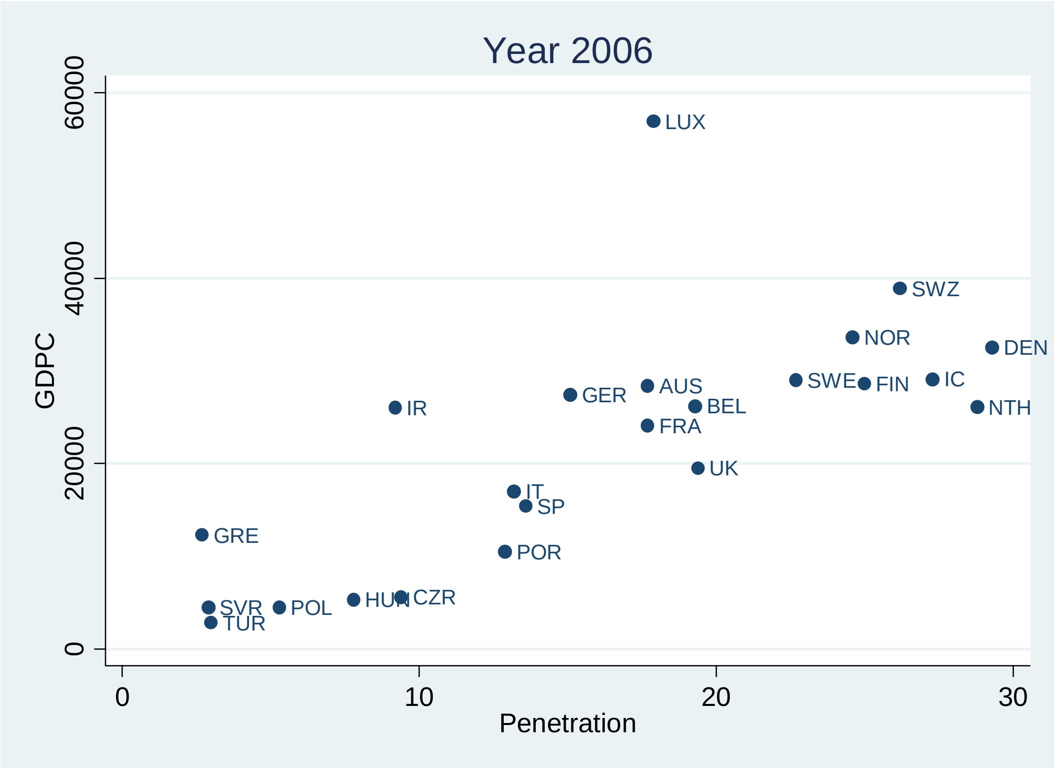
Table III

Variables and summary statistics

Variable	**Obs**	**Min**	**Max**
GDP (€ m)	60	27,439.2	2,423,800
GDPC (€)	60	15,900	65,700
Labor	60	0.29	39.04
Non ICT stock of capital	60	5,618.6	412,440
Broadband penetration	60	0.099	29.27
Education	60	10.66	34.63
Broadband price	60	1.4	213.74
Research and Development	60	341.84	49001.89
Urbanization	60	54.6	97.2
Broadband Investment	60	556.55	93,340.66
Deficit (% of GDP)	60	-86.9	17.6

Figure I

GDPC over Broadband Penetration in 2006 in the European Union



Results

The model is estimated using two different methods. The first incorporates single instrumental variable estimates which control for autocorrelation and heteroscedasticity consistency and the second uses nonlinear general method of moments system estimation. The limited information estimator (instrumental variables estimations on each equation) has the advantage of recognizing misspecifications in the equations. Thus the estimates of the other equations remain intact with the single equations estimates. However if the specification is correct the system estimators provide more precise coefficient estimates. The use of both specifications allows us to control for the correctness of the system specification and to obtain more insightful estimates from the model[10].

The results of the model are in table IV. There are four different estimations of the model equations. The first two columns of the table present the results for the single equation estimates and the two others the results for the three stages least squares estimates of the model. The first estimation of the model is a rather simplified one. It does not control for country fixed effects (column 1 table IV). From the econometrics point of view this can be translated into the intercept in the aggregate production equation (1) held constant. The estimated parameters for the aggregate production equation indicate that labor and capital are both positive and significantly associated with the GDP. In line with the growth literature, the education coefficient

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[10] J.M. Wooldridge, "Econometric Analysis of Cross Section and Panel Data", p.209-211

is significant and with a positive sign too. The elasticities for labor and capital are 0.034 and 0.973 respectively. For the same model when country and time fixed effects are taken into account the coefficients of labor and capital remain positive and significant. The education variable remains positive but significant at the 1% level with an increased coefficient.

The effect that we are trying to capture is mainly associated with the impact of the penetration rate in the aggregate production equation. From the first column of Table IV with the results, we can see that the coefficient of the penetration rate is significant and positive. This suggests that an increase in broadband adoption and use generates significant aggregate economic output. The magnitude of this effect can be calculated and result into a practical estimate of this positive relationship between broadband and GDP. The point estimate of the elasticity is roughly equal to 0.038 which implies that one percent increase in the penetration rate – described by the variable PEN in our model – increases economic growth by an average of 0.038 percent. The corresponding estimate for the fixed effects specification is 0.026. In order to get an idea of the magnitude of the result that we have calculated we first have to define a way to estimate the compounded annual growth rate (CAGR) for the penetration rate variable. This is the implied constant growth rate for a period of years that results in a defined future value. From our dataset we choose Spain which has a moderate increase in broadband adoption for the period 2003 – 2006 and we calculate this growth rate using the following equation:

$$CAGR_{PEN} = \left[\left(\frac{\frac{PEN_{2006}}{1-PEN_{2006}} - \frac{PEN_{2003}}{1-PEN_{2003}}}{\frac{PEN_{2006}}{1-PEN_{2006}}} \right) \hat{a}_3 + 1 \right]^{1/4} \quad (5)$$

In order to give a practical perspective to the estimation results we choose one country to check for their magnitude. Spain was 9^{th} in 2003 and 11^{th} in broadband penetration in 2006. This indicates that it had a medium-low position regarding penetration from the countries in the dataset. For the year 2003 Spain[11] had 5.49 percent of the population connected to some form of broadband service and by 2006 this had more than doubled reaching 13.63 percent. The compound growth rate for the broadband penetration was for this period equal to 25.5 percent and can be calculated by the equation:

$$PEN\_Growth = \left[\left(\frac{PEN_{2006}}{PEN_{2003}} \right) \right]^{1/4} - 1 \quad (6)$$

Using equation (5) and the preceding estimates of 0.038 and 0.026 we find that the compounded annual growth effect for Spain was roughly 0.59% and 0.40% respectively. Taking into account the random effects estimation we translate this value into the overall annual effect of fixed telecommunications infrastructure which

[11] For a full list of all country CAGR of Broadband Penetration and GDP see Appendix

implies that Spain's investment in broadband infrastructure for the years 2003 – 2006 boosted aggregate economic output by 0.59 percent annually. There are certainly important reasons to expect a contribution in economic output through broadband networks and the externalities that they create. This estimate attributes to them almost 10.4% a country's growth (since for Spain the average GDP growth rate at market prices for the fiscal years 2003-2006 was 5.70 percent[12]). Nevertheless Spain is one out of the fifteen-country dataset with lower and higher penetration rates and different effects on the CAGR. The example is intended to give a practical glimpse in this first model estimation and to provide the fertile ground for further research in the model and more detailed analysis. Besides, the bigger picture tells us that the EU15 countries have had an average 27.52 percent penetration increase for the period 2003-2006 and from this the 0.42% of their annual economic growth can be attributed to broadband infrastructure (almost one tenth of annual growth[13]).

The large effects that have been previously discussed are closely related to older studies that showed the extent of the return from public infrastructural investments. The results that are produced are consistent with the importance of telecommunications infrastructure and include possible externalities from the widespread availability of information. The estimated elasticity has to be controlled for parameters that have not yet been evaluated and have not been given the required attention. One explanation investigated below is that there is spurious correlation which suggests the use of a fixed-effects model. In other words we expect that the penetration variable picks up other growth promoting factors not yet taken into account in the aggregate growth equation.

[12] Source Eurostat and GDP data in euro per inhabitant at market prices, see Appendix for full dataset
[13] The average CAGR for the EU15 for the 2003-2006 period was 3.96%, see Appendix

Table IV
Estimates of the IV and 3SLS regressions

Variables	**IV GMM estimates**[1]		**3SLS estimates**[2]	
	(1)	(2)	(3)	(4)
GDP [3]				
Labor force	0.034***	0.497***	0.026	0.424***
	(2.89)	(4.27)	(1.35)	(3.01)
Non ICT stock of capital	0.973***	0.158***	0.976***	0.090*
	(74.44)	(4.32)	(46.25)	(1.91)
BB Penetration	0.038***	0.026***	0.067***	0.085***
	(4.22)	(6.46)	(3.51)	(7.51)
Education	0.058*	0.125***	0.045	0.063**
	(1.69)	(3.40)	(0.80)	(2.12)
Constant	1.568***	10.276***	1.523***	22.937***
	(8.20)	(35.07)	(6.53)	(7.90)
Penetration				
GDPC	0.221	5.565***	-0.349	5.863***
	(0.41)	(2.44)	(-0.83)	(5.08)
BB Price	-0.422***	-0.048	-0.342***	-0.037
	(5.92)	(-0.83)	(-5.84)	(-0.452)
Education	0.241	0.236	0.076	0.812
	(1.04)	(0.56)	(0.24)	(0.80)
R&D	0.058	3.900***	0.056	0.131
	(0.61)	(2.58)	(0.71)	(0.14)
Urbanization	1.841***	-2.634	1.693***	-0.079
	(3.87)	(-1.16)	(3.07)	(-0.03)
Constant	-7.940	-82.838***	-1.337	-61.488***
	(-1.32)	(-2.86)	(-0.38)	(-3.46)
BB Investment				
Deficit	-0.061***	-0.132***	-0.056***	-0.131***
	(-4.09)	(-5.30)	(-3.50)	(-9.84)
BB Price	2.281***	1.059**	2.328***	1.088***
	(17.90)	(2.27)	(15.07)	(4.09)
ΔPenetration				
BB Investment	0.346***	0.526***	0.087***	0.165***

	(1)	(2)	(3)	(4)
	(13.72)	(13.55)	(7.81)	(8.63)
R^2				
	(1)	(2)	(3)	(4)
Growth	0.98	0.99	0.99	0.99
Demand	0.52	0.95	0.51	0.95
Supply	0.84	0.98	0.84	0.99
Broadband Output	0.74	0.81	0.56	0.92

Number of observations: 60

(1) Random effects using single equation IV estimates[1]

(2) Fixed country and year effects using single equations IV estimates[1]

(3) Random effects using 3SLS GMM estimates with robust standard errors

(4) Fixed country and year effects using 3SLS GMM with robust standard errors

[1]Standard errors are clustered by country and year (robust estimates); the statistics are heteroscedasticity and autocorrelation consistent; the kernel used for the AC and HEC covariance estimation is the Newey West (Bartlett)

[2]Three Staged Least Squares estimates with endogenous variables GDP, Broadband Penetration, Broadband Investment and ΔPenetration

[3]Instruments used for the Broadband Penetration (Growth equation): Urbanization, Research and Development and Broadband Price.

[4]Asteriscs denote statistical significance (t-statistic) at the 1%,5%and 10% level

The focus of the empirical analysis conducted is not on the estimation of the demand and supply relationships in the broadband services market. However the need to control for them is very important. Therefore as can be seen from Table IV, it is very comforting that most of the remaining parameters are significant and robust across the specifications below. Getting back to our results the demand equation introduces some interesting insights to the discussion. While broadband price is negative and significant (table IV column 1) the GDPC is positive but insignificant and the education variable is positive and insignificant as well. However we have already accounted for the education level in the growth equation and here we are measuring the effect of education on broadband only and not the overall effect of education as a growth factor of the economy. Nevertheless the educational level of the population is a critical enabler for all internet and high technology applications. The expected sign is found in the research and development investments but the value is relatively insignificant. One of the most significant variables determining the level of broadband penetration is the urbanization variable. The estimated coefficient is roughly 1.84 and translates into 1.84 percentage point of penetration increase for every 1 percentage of the population migrating from a rural area to a large city. This is also attributed to the amount of infrastructural investment in the larger cities from the telecom providers and also the ‘thirst’ for certain services that the city lifestyle creates for its inhabitants. A final comment on the demand equation is that it is largely affected by the purchasing power of the population and the price of the service as well as the attractiveness of larger cities.

Turning to the supply equation we find that there is a positive and significant relationship between broadband price and broadband investment. The level of government deficit is also significantly related to telecommunications investment across the European Union. It is intuitive that telecommunications infrastructure investment should be positively affected by the government surplus in the European Union since it would trigger a change for further investments in this sector. However we find a strongly negative relationship indicating that countries with a larger deficit invest more in broadband than countries with a surplus do. There are some possible explanations for this phenomenon. One of them supports that broadband infrastructure investment – at least from the incumbent operators that are still semi private – is part of a larger spending program that runs in the specific country and therefore creates a greater deficit. As a result the existence of the deficit is not an impediment to the investment in telecommunications infrastructure. Another explanation is that the countries that experience strong surplus are the most advanced in terms of broadband penetration (Denmark, Finland and Sweden) and the large sum of the required investments have already been capitalized by the popular participation. Therefore the rest of the countries experience both strong deficits (Germany, France and UK) and large investments in broadband infrastructure.

The last equation reported in Table IV is the production function relating investment and penetration rate. The context of this equation is that the difference in the stock of penetration – the flow of annual broadband penetration – is related to the flow of broadband investment. The relationship between investment and penetration is – as expected – positive and significant. This actually is the most direct relationship found in the whole of this four equations model. The difference in broadband subscribers is attributed to the investment for infrastructure that facilitates this increased demand and participation. The coefficient here is equal to 0.346 which implies that € 2.89m is “needed” for 1 percent increase in the difference in broadband penetration level. Of course broadband penetration does not measure the investment per se but the participation of the population in broadband networks. However it is a good indicator that shows how much investment affects infrastructure (directly) and consequently participation (indirectly). In other words if the penetration in Y1 is 10 percent and the expected penetration in Y2 is 13 percent, if we (as private infrastructure investors) invest € 2.89m more on the infrastructure, the penetration in Y2 is going to be 14 percent. Again this is an indication and not an actual calculation and takes into account all countries. This value might be larger for Greece (which lacked backhaul network infrastructure) and smaller for Denmark (which could deploy network expansions a lot cheaper).

We have already mentioned that much of the spurious correlations found in previous single equation studies as well as random effects experiments disappear once they are econometrically controlled for fixed effects (country and time). To test if this is also apparent in our model we re-estimate the model allowing for a country and time specific intercept in all equations. The results are reported in column (2) of Table IV.

As we can see from the results in Table IV most of the parameter estimates change only slightly. For the first equation we can see that there is a remarkable change in the labor force coefficient but not in its significance once the intercept is not any more held constant. The effect is still positive but now significant and the coefficient increases from 0.034 to 0.497. This can be partially attributed to the random effects estimation that yields a lot less to labor force than it actually accounts for. The capital coefficient remains positive and significant but now reduced to 0.158. Education becomes significant to the 1% level and remains positive. Since the other estimates remain almost the same we do not discuss them again. The important for our research penetration rate coefficient changes as well. The initial value of 0.038 in the random effects model becomes now 0.026. This change is not a remarkable one but as suggested by the discussion previously, it was expected. The significance changes for the broadband penetration rate without altering anything else in the equation. Moreover the implied growth effects are more reasonable than before. If we use the example of Spain again with the new value for broadband penetration we find that the impact of broadband infrastructure on aggregate economic growth to be at a compounded annual effect of 0.38 percent. For the EU15 countries average this amount is equal to 0.40 percent of the gross national product annually. Given that the EU15 countries have grown at a compounded annual growth rate of 4 percent for the period 2003 – 2006, our fixed effects estimate implies that about 9.8 percent of the growth can be attributed to the high speed internet service and telecommunications industry (almost one tenth of the annual growth).

As a matter of fact, it can be said that the fixed-effects estimates are more reasonable. There are various studies that point out the importance of the ICT technologies as a whole – not particularly for broadband – on economic growth that find almost the same or higher returns from the broadband investments. They are also similar to older studies relating the returns from public infrastructure to the telephony network that can be considered a subset of the modern broadband networks. As a general note, it appears that the resulting coefficients are much smaller and their impact is found to be less once simultaneities and fixed effects are controlled for.

The discussion about the other three equations will be brief for the moment. The supply and output equations have almost the same coefficients and significance. There is an important change in the supply equation and has to do with the parameter of broadband price. It appears that broadband prices have a positive but much less important – in terms of coefficient – impact on the amounts invested in the telecommunications sector. The coefficients in the demand equation are generally different from those reported in the random effects model. The purchasing power coefficient becomes larger in the fixed effects model estimation and is now significant. The once dominant broadband price variable now becomes less significant and its coefficient shrinks even more. The second most important variable in this equation is the education. It still remains positive and insignificant indicating a problematic behavior that can either be attributed to the data or the particular variable used. Urbanization is negative and insignificant in this specification. The research and development variable becomes significant and continues to have a positive sign. In other words the amounts invested in R&D positively affect broadband participation. We should mention here that this variable represents all the research funds in a country from private or public R&D and not those directed to ICT.

The last two columns of the table IV include the three staged least squares estimates for the simultaneous equations model. The reason for these estimates is first to check whether there is a significant misspecification in the single equations and second to provide some more precise estimates of the coefficients. In order to check for the correctness of the equations and their structure we need to compare the instrumental variable single equations results for each of the random and fixed effects specifications. In terms of statistical significance the random effects estimates are very encouraging. One crucial difference is found in the labor force coefficient which becomes insignificant in the fixed effects full model estimation. In terms of coefficients the values are also very similar. There is no observation that allows us to point out a misspecification in the system of equations. The fixed country and time effects account for all other events or elements that affected the results in the specific country clusters in each year. Therefore these estimates should be considered more objective than the latter. Again in terms of statistical significance the results seem to give the same impression with the single equation estimates. One obvious change is related to the significance of the research and development expenditure which now becomes insignificant. All other changes are marginal. However the coefficients do change in certain cases. Especially in the growth equation the non-ICT stock of capital and the education coefficients seem to dwindle to the half of their IV estimate and the broadband penetration estimate increases substantially. A more general observation that spreads across all estimates has to do with the output equation. We can see that in the 3SLS specification the coefficients for the relative importance of broadband investment against the difference in broadband penetration shrink substantially in both random and fixed effects estimations. This might show that although the infrastructural investments are crucial for the overall penetration their significance drops when we account for other broadband penetration promoting factors like the GDPC. The situation in table IV does allow for some discussion about the relative strengths of the model. It is possible that there are certain limitations either based on the structure of each equation or the dataset itself but there is not a clear reason to contradict its correctness.

BROADBAND CRITICAL MASS

The public and private infrastructure discussion showed that investments in broadband technologies have different network externalities from the transportation and utilities investments. They entail the important network effects and positive externalities that spread way beyond the actual infrastructure itself. These effects include the applications that derive from the utilization of the infrastructure and the participation of large chunks of the population. The levels of participation largely affect the value of the network and define certain milestones in its evolution. These levels are not clearly defined by rigid thresholds but by areas of importance. An implication of network externalities is that the impact of telecommunications and broadband infrastructure on growth will not be linear – thus resulting in larger than proportional returns for certain broadband penetration levels. These levels, hereafter critical masses, allow us to estimate the increasing returns whenever each of them is actually reached.

It is worth emphasizing that the initial model specification does not allow for such controls. The primary intention was to understand and estimate this effect of broadband penetration on aggregate output not the vice versus relationship. The rationale followed the idea of distinguishing those effects from each other so that the simultaneity bias would be avoided. Nevertheless the final goal is to evaluate the one way relationship pointed out in the aggregate production equation. Arguably the externalities of the telecommunications networks are primarily responsible for the nonlinearities or the technological diffusion that is taking place at the same time in the broad ICT industry. In order to test for the existence of certain nonlinearities in our model we have to introduce some structural changes in the equations. What we want to capture is the level that these changes happen and to get some idea about the extent of this change. Hence our results about these externalities are only suggestive. The following modification in the aggregate production equation will allow us to measure the previously mentioned phenomenon. Equation (1) becomes:

$$\log(GDP_{it}) = a_0 + a_1 \log(K_{it}) + a_2 \log(LF_{it}) + (a_3 LOW + a_4 MEDIUM + a_5 HIGH)\log(PEN_{it}) + a_6 EDU_{it} + \varepsilon_{it}^{1} \quad (7)$$

The three dummies LOW, MEDIUM and HIGH correspond to a low, medium and high penetration level. The countries that experience the low, medium and high penetration levels are defined in list 1. In particular, 53 percent of the countries in the dataset have a medium penetration level and almost 27 percent of them have high penetration. The remaining 20 percent is classified as low penetration. The threshold below 10 percent is used for the low penetration level, between 10 percent and 20 percent is used for the medium broadband penetration and the threshold of more than 20 percent for the high[14]. We note here that penetrations reaching more than 50 percent of the population are not yet experienced which translates into one broadband connection per house (with an average of two people leaving in a house). This idea takes into account the sharing of the same line by more than one person which is apparent in land line telephony as well.

List I

Country clustering according to penetration levels

Low Penetration (<10%)	**Medium Penetration (>10% and <20%)**	**High Penetration (>20%)**
Greece	Austria	Denmark
Ireland	Belgium	Finland
Portugal[15]	France	Netherlands
	Germany	Sweden
	Italy	
	Luxemburg	
	Spain	
	UK	

[14] It is worth stating that the penetration levels are defined by the latest year data. This means that if some countries reach the medium level penetration in 2006 then they are included in the medium penetration cluster – no matter what the initial penetration levels were (in the previous years). This is because the levels themselves do affect the returns. Of course countries that have been in the medium or high penetration cluster for all years are expected to have higher returns than those migrating to the higher levels during the years.

[15] Portugal is the only exception in the rule of 2006 penetration level. It actually has a 12.9% penetration for the year 2006 but it is included in lowest penetration cluster because it has an average penetration for the four years around 7%. Countries with similar but slightly better performance are Spain and Italy. The clustering has been tested when these were in the low penetration segment and did not produce any noteworthy changes.

The modified equation (7) allows for country and time fixed effects. We are mainly interested in the significance and relative magnitude of the three coefficients of penetration (a_3, a_4, a_5). In the random effects and fixed effects model estimation, the penetration coefficient was always positive and significant. Therefore if the a_3 is found now positive and significant and a_4 and a_5 are negative we have support for the diminishing returns hypothesis. On the other hand, if the signs of a_4, a_5 are reversed, thus making them both positive and significant then we have evidence to support the "critical mass" argument, in that the impact might be relatively insignificant for low penetration rates. It is important to mention that most countries have actually climbed from medium to high penetration or from low to medium penetration levels. This effect is time sensitive and the introduction of the time fixed effects absorbs some of the change which would overestimate the coefficients of the separate penetration levels.

The estimation results for the new system of equations which in turn results in two new models are given in Table V. We are only estimating fixed effects for these models since we believe in the results that account for the time and country specificities. The first column includes the single equation IV results that account for autocorrelation and hetreroscedasticity. Most of the estimates remain unchanged and thus we are not going to discuss all of the again. The most significant change is found in the demand equation where the research and development coefficient becomes insignificant for the 3SLS estimation. Otherwise the changes are marginal. Our attention will focus on the 3SLS coefficients which should be considered more precise. Turning into the reported parameters we find that the coefficient for the low penetration rate is around 0.025. This could show the effect of broadband penetration for low level countries which according to equation (5) is 0.51%. The significance is high (t-statistic of 6.58) thus indicating the effects are in place for these levels of penetration. The next coefficient corresponds to the medium penetration level. The t-statistic is at the one percent level (3.67) indicating again stronger effects achieved for countries between the penetration thresholds of 10 and 20 percent. The parameter is also low and equal to 0.029 which translates into a low added value on top of what can be achieved by low penetration countries. The corresponding effect is 0.45%. We can see a clear difference between low and medium penetration countries here. For the high level penetration coefficient we find a remarkable value both in terms of magnitude and significance. The new value is equal to 0.063 and a t-statistic of 5.84, indicating strong effects. This effect unveils the criticality of the 20 percent threshold. This indication is supported by the fact that in the dataset some countries only marginally achieved it. The 20 percent- penetration rate tells us that almost 50 percent of the population has access to the network. This yields an important effect on top of what the actual network can achieve. It also indicates the existence of the aforementioned externalities and supports the concept of critical mass. It indirectly creates a vision for countries to achieve these goals and capitalize the beneficial effects that the network can provide. It also implies a 0.89% aggregate growth rate due to broadband externalities.

Table V

Estimates of the IV and 3SLS regressions for the broadband penetration clusters and the squared component

Variables		IV GMM estimates[1]	3SLS estimates[2]	3SLS estimate with squared component
		(1)	(2)	(3)
GDP [3]				
Labor force		0.389***	0.329***	0.330*
		(4.56)	(3.52)	(1.88)
Non ICT stock of capital		0.075***	0.073**	0.071
		(2.42)	(2.20)	(1.29)
BB Pen Squared		-	-	0.007**
				(1.87)
BB Penetration	low	0.024***	0.025***	
		(6.99)	(6.58)	
	medium	0.031***	0.029***	0.120***
		(3.39)	(3.67)	(5.44)
	high	0.068***	0.063***	
		(6.02)	(5.84)	
Education		0.026	0.019	0.038
		(1.57)	(0.94)	(0.85)
Constant		11.825***	12.079***	11.909***
		(47.22)	(40.24)	(17.90)
Penetration				
GDPC		5.565***	6.362***	5.455***
		(2.44)	(5.23)	(4.28)
BB Price		-0.048	-0.043	-0.017
		(-0.83)	(-0.090)	(-0.33)
Education		0.236	-0.199	-0.322
		(0.56)	(-0.52)	(-0.77)
R&D		3.900***	1.342	0.687
		(2.58)	(1.49)	(0.76)
Urbanization		-2.634	-0.667	-0.131
		(-1.16)	(-0.25)	(-0.05)
Constant		-82.838***	-78.906***	-58.209***

	(1)	(2)	(3)
	(-2.86)	(-4.48)	(-3.27)
BB Investment			
Deficit	-0.132***	-0.129***	-0.130***
	(-5.30)	(-9.53)	(-9.76)
BB Price	1.059**	1.0128***	1.116***
	(2.27)	(4.20)	(4.19)
ΔPenetration			
BB Investment	0.526***	0.165***	0.165***
	(13.55)	(8.65)	(8.63)

R^2	(1)	(2)	(3)
Growth	0.99	0.99	0.99
Demand	0.51	0.95	0.95
Supply	0.84	0.99	0.99
Broadband Output	0.56	0.92	0.92

Number of observations: 60

(1) Fixed country and year effects using single equations IV estimates[1]

(2) Fixed country and year effects using 3SLS GMM with robust standard errors

(3) Fixed country and year effects using 3SLS GMM with robust standard errors

[1]Standard errors are clustered by country; the statistics are heteroscedasticity and autocorrelation consistent; the kernel used for the AC and HEC covariance estimation is the Newey West (Bartlett)

[2]Three Staged Least Squares estimates with endogenous variables GDP, Broadband Penetration, Broadband Investment and Difference in Penetration

[3] Instruments used for the Broadband Penetration (Growth equation): Urbanization, Research and Development and Broadband Price.

According to the estimates from the relative penetration levels from Table V we can assemble the estimated returns from the investments in broadband infrastructure in each country for the period 2003 – 2006. These estimates are less generic since they take into account only country and time fixed effects estimates and account for the scalable benefits earned through the various penetration levels. Table VI summarizes these estimates.

Table VI

Percentage of impact of broadband infrastructure on growth for each country in each cluster

	Average GDP growth	Average % impact of broadband infrastructure on GDP	Percentage of country's growth attributed to broadband infrastructure
BB Penetration >20%			
Netherlands	3.33	1.04	31.25
Denmark	3.66	0.99	27.04
Finland	4.08	1.06	26.03
Sweden	3.67	0.92	25.04
BB Penetration <20% and >10%			
Germany	2.32	0.48	20.70
Italy	2.49	0.51	20.63
France	2.88	0.50	17.46
UK	3.78	0.55	14.59
Austria	3.67	0.45	12.17
Belgium	3.48	0.32	9.23
Spain	5.70	0.46	7.99
Luxemburg	7.68	0.60	7.85
BB Penetration <10%			
Portugal	3.04	0.41	13.47
Greece	5.52	0.60	10.83
Ireland	5.95	0.57	9.55
EU Average			
EU - 15	4.08	0.63	16.92

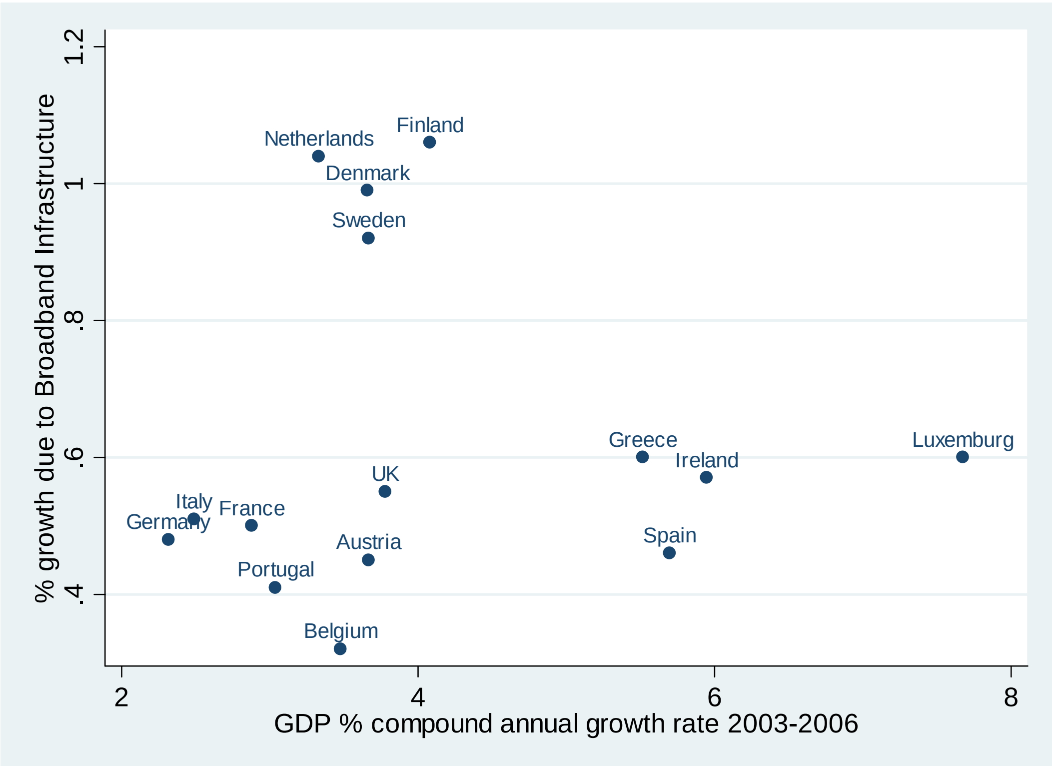
Another way to identify the existence of several different levels of return from broadband infrastructure based on the penetration rate is presented below. The inclusion of a quadratic penetration term in the aggregate production equation is used as an indication of increasing returns from higher penetration or decreasing ones. The parameter coefficient a_4 is used as the key to identify this value. The aggregate equation is modified in the following form:

$$\log(GDP_{it}) = a_0 + a_1 \log(K_{it}) + a_2 \log(LF_{it}) + \\ a_3 \log(PEN_{it}) + a_4 (\log(PEN_{it}))^2 + a_5 \log(EDU_{it}) + \varepsilon_{it}^{1}$$

(10)

The results are included in Table V column 3. We can see that the quadratic term has a positive and significant coefficient thus indication significant returns to scale. The rest of the terms are not discussed here because this regression is used as a test to reassure about the methodology of the penetration levels used previously.

Figure II
GDP growth rate and the relative returns on growth based on the broadband infrastructure



Conclusion

The results suggest that there are increasing returns to broadband telecommunications investments which are consistent with the persistence of network externalities. What has been seen is that there is evidence of a critical mass phenomenon in broadband infrastructure investments. The level that has been identified as critical is the 20% which effectively translates in half of the population having access to a broadband connection. The econometric specification showed that these effects exist in the Scandinavic countries which enjoy higher returns from their increased participation.

The limitations of this study are mainly related to data availability. The rapid spread of broadband technologies in the recent past has not yet allowed for wide availability of micro level qualitative data that focus on different aspects of the technology. For example there is little information about broadband usage and the types of services that customers choose more frequently based on their socio-economic background. On the theoretical part the level of infrastructure that is required in order to achieve a critical mass can not always be the same for every country. Perhaps wealthier and more urbanized countries benefit faster from the broadband services because of the economies of scale of the networks.

This study acts as a starting point for the macroeconomic impact of fast network access technologies on economic growth. An interesting future study could use data from the all EU27 and other developed and developing countries which are in different growth phases from the core EU15. Richer and more descriptive variables could be incorporated like the way each individual sector benefits from the usage of different broadband platforms and the ways the spillovers are handled and achieved.

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APPENDIX

Compound annual Growth rates for GDP per Capita, Broadband Price and Broadband Penetration (constant 2000 prices)

	GDP (€ m)		CAGR % (2003-2006)	BB Price 1 Megabyte per second (€)		CAGR % (2003-2006)	Broadband Penetration		CAGR % (2003-2006)
	2003	2006		2003	2006		2003	2006	
Austria	236149.1	272766.4	3.67	73.94	15	-32.89	7.58	17.75	23.70
Belgium	289690	332133	3.48	14.91	12.1	-5.09	11.74	19.34	13.29
Denmark	197069.9	227568.2	3.66	75.502	6.75	-45.32	13.02	29.27	22.45
Finland	152345	178759	4.08	85.651	5.5	-49.66	9.50	24.97	27.33
France	1660189	1859981	2.88	80.344	3.6	-53.99	6.08	17.71	30.64
Germany	2211200	2423800	2.32	53.902	5.1	-44.54	5.58	15.09	28.24
Greece	185225	229599.8	5.52	213.74	26	-40.94	0.09	2.69	133.82
Ireland	148501.7	187097.3	5.95	156.76	17	-42.61	0.84	9.17	81.77
Italy	1391530	1535540	2.49	113.70	3	-59.70	4.14	13.15	33.50
Luxemburg	27439.2	36889.5	7.68	149.75	18	-41.12	3.41	17.94	51.45
Netherlands	491184	559852	3.33	53.114	1.4	-59.71	11.79	28.84	25.06
Portugal	144128	162489.5	3.04	143.67	9	-49.97	4.80	12.90	28.04
Spain	841042	1049848	5.70	189.66	20	-43.01	5.49	13.63	25.53
Sweden	287689.4	332302.6	3.67	28.67	2.3	-46.78	10.69	22.66	20.66
UK	1745051	2024026	3.78	86.815	6.3	-48.10	5.33	19.42	38.16