How Important are Mobile Broadband Networks for Global Economic Development?

Harald Edquist
Ericsson Research

Peter Goodridge
Imperial College Business School

Jonathan Haskel
Imperial College Business School

Xuan Li
ISS Ethix

Edward Lindquist
Business Sweden

Paper prepared for the 35th IARIW General Conference

Copenhagen, Denmark, August 20-25, 2018

Session 6C-1: Is Productivity Growth Slowing Down? II

Time: Friday, August 24, 2018 [9.00-12.30]

How Important Are Mobile Broadband Networks for the Global Economic Development?*

By

Harald Edquist**, Peter Goodridge***, Jonathan Haskel****, Xuan Li***** and Edward Lindquist******

July 30, 2018

Abstract

Since the beginning of the 21st century mobile broadband has diffused very rapidly in many countries around the world. This paper investigates to what extent the diffusion of mobile broadband has impacted economic development in terms of GDP. The study is based on data for 135 countries (90 countries once controlling for capital, employment and human capital) for the period 2002–2014. Based on a two stage model we are able to conclude that on average a 10 percent increase of mobile broadband adoption causes a 0.8 percent increase in GDP. Moreover, once we control for the years since mobile broadband was introduced, we find that the economic effect gradually decreases over time. For the country with median average growth of mobile broadband penetration, this implies that the economic effect has disappeared 6 years after introduction (if introduction is defined as a mobile penetration of 1 percent).

JEL *Codes:* F62; O11; O33; O47

Keywords: ICT, Mobile broadband, Economic growth, Instrumental variables

---

* We are very grateful to the ERSC, grant number, ESRC IAA PSB111_MSRH and Ericsson Research for funding the research project "The Economic Impact of Communication Equipment".
** Corresponding author: Harald Edquist, Ericsson Research, Torshamnsgatan 23, SE-164 83, Stockholm, Sweden. Email: harald.edquist@ericsson.com.
*** Peter Goodridge, Imperial College Business School, Imperial College, London SW7 2AZ, United Kingdom. Email: p.goodridge10@imperial.ac.uk
**** Jonathan Haskel, Imperial College Business School, Imperial College, London SW7 2AZ, United Kingdom. Email: j.haskel@imperial.ac.uk
***** Xuan Li, ISS Ethix AB, Stureplan 4C, SE-114 35, Stockholm, Sweden. E-mail: xuan.li@issethix.com
****** Edward Lindquist, Business Sweden, Klarabergsviadukten 70, SE-111 64, Stockholm, Sweden. Email: edward.lindquist@business-sweden.se

1. Introduction

Throughout history, new technology has always been an important driver of productivity and economic development. We are currently experiencing a technological revolution based on ICT. One of the major innovations within ICT, during the last decade, is the use of mobile broadband. According to GSMA (2018) mobile broadband connections have increased from approximately 27 thousand in 2001 to 4.8 billion in 2017 i.e. an average growth of 113 percent per year.[1]

The use of data being sent via mobile networks has been increasing exponentially at approximately 65 percent on a year-on-year basis during the period, 2010–2015 (Ericsson mobility report 2016; Coyle and Williams 2011). The basis for this development has been the introduction and expansion of 3G and 4G mobile network systems and the development of smartphone devices.

Despite the enormous expansion of mobile broadband, it is still unclear to what extent, it has contributed to global economic development. Previous research has shown that ICT has had a large economic impact in many countries (Brynjolfsson and Hitt 2003; Oliner and Sichel 2000; Röller and Waverman 2001). However, most of these studies have focused on established technologies such as fixed telephone lines and computers. Only a handful of studies have focused on mobile technologies (see for example Gruber and Koutroumpis 2011). As more data becomes available it has become increasingly easy to also study the impact of newer technologies. This paper investigates the macroeconomic impacts of mobile broadband based on econometric methods applied to a cross-country panel data set. The primary questions that will be investigated are:

- To what extent has mobile broadband affected macroeconomic development in terms of GDP globally?
- If there is an impact from mobile broadband, is it an effect of mobile broadband introduction and/or a gradual process along mobile broadband penetration?

[1] GSMA (2018) defines mobile broadband connections as SIM cards registered on a mobile network in a device capable of download speeds of 256 kb/s or greater, including 3G (e.g. WCDMA, HSPA) and 4G (e.g. LTE, WiMAX) network technologies.

Chinn and Fairlie (2007) pointed out that there is a digital divide across countries in personal computers and Internet penetration. Thus, our questions are important from a policy perspective, because if mobile broadband has an important economic impact many countries could leapfrog in their economic development. We therefore also investigate the impact from mobile broadband in high- and low-income countries and OECD and non-OECD countries.

The paper shows that mobile broadband is positively associated with GDP based on 135 countries (90 once controlling for capital, employment and human capital). Introducing a dummy variable for mobile broadband introduction in a difference-in-difference specification, there is evidence of an introductory effect from mobile broadband. Moreover, there is also a contemporaneous effect from mobile broadband penetration. Furthermore, based on moving averages, we find stronger and larger effects from five-year differences compared to first differences. This is an indication that a lagged effect from mobile broadband penetration on GDP also exists.

Based on a two stage model controlling for simultaneity and reverse causality, we find strong evidence that mobile broadband introduction and penetration causes GDP growth rather than vice versa. The results suggest that a 10 percent increase in mobile broadband penetration causes a 0.8 percent increase in GDP. Moreover, once we control for the years since mobile broadband was introduced, we find that the economic effect gradually decreases over time. Finally, we find that our results are robust once we distinguish between low- and high-income countries. However, the effect from mobile broadband on GDP is considerably larger and more significant in non-OECD countries compared to OECD countries.

The paper is organized as follows. In section 2 we summarize findings from earlier research and position our study in the current literature. In section 3 we present the methodological framework, in section 4 we describe the data, in section 5 and 6 we present our results based on both a fixed effect and an instrumental variable approach. Section 7 provides robustness checks and section 8 concluding remarks.

2. Related Literature

2.1 The economic impact of communication technology

Throughout, the 1980s it was unclear to many economists to what extent information and communication technology (ICT) impacted economic growth at the macro level (Solow 1987). However, ever since economic and productivity growth took off in the US economy in the mid-1990s, there have been a plethora of studies showing links between ICT and economic development (see for example Oliner and Sichel 2000; Jorgenson et al. 2008; O'Mahony and Vecchi 2005; van Ark et al. 2008). Most of these studies focused on ICT generally, while the impact of different ICT-technologies was less emphasized.

In the 1980s, fixed telephones were already found to have strong contribution to economic development (Hardy 1980). Moreover, Röller and Waverman (2001) found evidence of a significant positive causal link from telecommunication infrastructure on aggregate output, based on data in 21 OECD-countries spanning from 1970–1990. Similar results were found by Datta and Agarwal (2004).

Based on the growth accounting framework, Corrado (2011) found that communication equipment capital deepening accounted for 7 percent of labor productivity growth in the US non-farm business sector in 1995–2007. Moreover, Goodridge et al. (2014) estimated that the contribution from communication equipment to value added growth in the UK was 5 percent (i.e. 0.11 percentage points per annum) from 2005–2008.

A few studies have taken a more focused approach looking at mobile communication. Waverman et al. (2005) found that mobile telephony had a positive and significant impact on growth in developing countries. Moreover, Gruber and Koutroumpis (2011) investigated the contribution from mobile telecommunication infrastructure to economic growth from 1990–2007. Their findings showed that investment in mobile telecommunication infrastructure had a considerable contribution to economic and productivity growth.

Since the mid-2000s the speed of uploading and downloading data from mobile devices has increased tremendously. The increase in data traffic was 65 percent per year from 2010–2015 (Ericsson mobility report 2016). The basis for this development has been the introduction and expansion of 3G and 4G mobile network systems and the development of smartphone devices.

Thus far little is known about the economic impact of mobile broadband however several papers have investigated the relationship between fixed broadband and economic growth. Czernich et al. (2011) found that after a country has introduced fixed broadband, GDP per capita was between 2.7 and 3.9 percent higher on average than before introduction. Moreover, a 10 percentage point increase in broadband penetration was associated with increased annual per capita growth of 0.9 to 1.5 percentage points.

Qiang and Rossotto (2009) found that fixed broadband penetration was associated with an increase in GDP per capita of 1.2 and 1.4 percent in developed and developing countries, respectively. Based on different specifications Koutroumpis (2009) found broadband penetration to have a significant impact on GDP growth. Rohman and Bohlin (2012) also found that a doubling of broadband speed contributed 0.3 percentage points to growth compared with growth in the base year.

Williams et al. (2012) is one of the few studies thus far that has investigated the impact of 3G penetration on economic growth. Their findings showed that for a given level of total mobile penetration, a 10 percent substitution from 2G to 3G increases GDP per capita growth by 0.15 percentage points. Williams et al. (2012) also showed that a doubling of mobile data use, results in a 0.5 percentage points increase in GDP per capita.

2.2 Why would mobile broadband have an economic impact?

From 2001 to 2017 the annual growth rate of mobile broadband connections has been 113 percent. Meanwhile, the share of mobile broadband connections in total connections have increased from 0.003 percent to 61.1 percent. There are a number of reasons why we would expect this rapid diffusion to have a substantial impact on macroeconomic development.

Mobile broadband enables a faster distribution of information and new ideas. Generally, mobile broadband may be a substitute for fixed broadband, while fixed broadband is not a substitute for mobile broadband (Stork et al. 2014). This implies that anyone with a mobile broadband connection can access information wherever they are which should give rise to large productivity increases.

Mobile broadband will also have a large effect on competition. It enables consumers to compare prices and conduct market transactions wherever they are. Increased competition has a positive impact on productivity and growth through more efficient use of resources (Nickell 1996). Moreover, increased competition will also facilitate entrepreneurial ideas as entry of new firms becomes easier and incentivizing firms to innovate (Bloom et al. 2016; Aghion et al. 2005).

A number of studies have found stronger effects from investments in mobile telecommunications adoption in developing countries than in developed countries (Waverman et al 2005; Sridhar and Sridhar 2007; Thompson and Garbacz 2007). These findings suggest that many developing countries have been able to leapfrog by focusing on investments in mobile rather than fixed infrastructure. Moreover, being able to use the mobile technology for improving payments creates huge opportunities for developing countries to reduce transaction costs (Jack and Suri 2014).

3. Methodology: Production function framework and econometric specification

The model applied in this paper is based on the framework of the neoclassical production function. The production function framework relates output to labor, capital, intermediate inputs and TFP. In this paper we measure output as GDP, which is obtained by deducting intermediate inputs from gross output and adjusting for subsidies and sales taxes. Assuming an augmented Cobb-Douglas production function, we have the following equation:

$$Y_{i,t} = TFP_{i,t} K_{i,t}^{\beta_K} L_{i,t}^{\beta_L} \qquad (1)$$

where $Y_{i,t}$ is real GDP, $K_{i,t}$ is capital , $L_{i,t}$ is labor input and *TFP* is Hicks-neutral total factor productivity, all for country *i* at time *t*.

By taking natural logarithms of equation (1) we have:

$$\ln Y_{i,t} = \beta_K \ln K_{i,t} + \beta_L \ln L_{i,t} + \ln TFP_{i,t} \qquad (2)$$

where β represents the output elasticity of each input.

In our econometric specification, we have also added a measure of human capital as a control variable. Thus, to test whether there is a direct impact when mobile broadband is introduced we use the following difference-in-difference econometric specification:

$$\ln Y_{i,t} = \beta_0 + \beta_I D_{i,t} + \beta_K \ln K_{i,t} + \beta_L \ln L_{i,t} + \beta_{HK} \ln HK_{i,t} + \partial_t T_t + (a_i + \varepsilon_{\mathrm{i.t}}) \tag{3}$$

T_t is a set of year dummy variables included in order to control for common shocks. Finally, a_i is a set of unobserved country specific effects and $\varepsilon_{i,t}$ is the error term.

There are two possible effects of mobile broadband. First, there may be a permanent shift in the GDP level once mobile broadband has been introduced. This could be explained by the effect from early adopters, but also from the increase of large initial investments due to mobile broadband roll-out. To model this, we follow Czernich et al. (2011) by including a dummy when mobile broadband is introduced in a country.[2] The dummy variable equals one if the penetration rate is greater than or equal to 1 percent. Japan and South Korea were the first countries to reach a penetration rate of more than one percent in 2003. However, using the one percent penetration rate as a threshold for introduction might seem arbitrary; therefore, we also introduced a five percent penetration level as an additional threshold.

Second, mobile broadband may also positively affect economic growth by continuously spurring the innovation processes (Czernich et al. 2011). In order to estimate the continuous effect of mobile broadband penetration, we replace the dummy variable of mobile broadband introduction with a continuous variable of mobile broadband penetration rate:

$$\ln Y_{i,t} = \beta_0 + \beta_{MB} \ln MB_{i,t} + \beta_{YI} YI_{i,t} + \beta_K \ln K_{i,t} + \beta_L \ln L_{i,t} + \beta_{HK} \ln HK_{i,t} + (a_i + \varepsilon_{\mathrm{i.t}}) \tag{4}$$

where $MB_{i,t}$ is mobile broadband connections expressed as a percentage of total connections. The reason we use the log of the mobile broadband ratio is because we assume diminishing marginal returns to technology. This implies that by taking the log of the ratio we assume that the economic impact of the first connections are more important than connections at a later stage. The rationale behind this would be that the persons with the highest marginal returns are the first ones to adopt the new technology. Moreover, since we measure mobile broadband in terms of MBB connections in total connections it also makes sense to use the log

[2] Czernich et al (2011) use this rule only for the predicted values based on their two-stage model. However, we use the same rule also for our non-predicted values. The reason is that we find that there might be a considerable risk of measurement errors with very low penetration of mobile broadband. Both approaches provide similar results (see section 5).

specification as the economic value of a second connection for the same person probably is considerably lower.

We also include an additional control variable $YI_{i,t}$ showing the number of years since mobile broadband was introduced. This variable then accounts for faster diffusion in countries that introduce broadband later. According to Gerschenkron (1952) “relative backwardness” may facilitate economic growth, since it is easier to imitate the technologically leading countries. Since we control for the years since introduction we do not include year dummy variables. According to Wooldridge (2009) it is not possible to estimate the effect of any variable whose change across time is constant if year dummy variables are included.

We use two methods for controlling for country-specific effects. The first method is within-groups regression, where the mean values of the variables in the observations of a given country are calculated and subtracted from the data of that country. This removes the unobserved effect. The model explains the variation around the mean of the dependent variable in terms of the variations around the means of the explanatory variables for the group of observations for a given country.

The second method takes the first difference of equation (4), which also removes the unobserved country-specific effects.[3] The new equation can be written:

$$\Delta \ln Y_{i,t} = \beta_0 + \beta_{MB}\,\Delta \ln MB_{i,t} + \beta_K \Delta \ln K_{i,t} + \beta_L \Delta \ln L_{i,t} + \beta_{HK}\,\Delta \ln HK_{i,t} + \delta_t + v_{\mathrm{i.t}} \quad (5)$$

where δ_t are year dummies, which capture common economic shocks, and $v_{i,t}$ is the differenced residual.

Finally, we set out an instrumental variable approach in section 6 below.

[3] Based on data over two years the within group estimation and first differences are identical. When more than two years are analyzed the two methods do not yield the same result but they are both unbiased estimators under the underlying coefficient vector. However, when there is no serial correlation of the idiosyncratic errors, within group estimation is most efficient. If the error terms follow a random walk process, then first differencing is more efficient (Wooldridge 2009).

4. Data

The data used in this paper has been collected from a number of different sources. Data on GDP, employment and human capital were retrieved from the Penn World Tables (Feenstra et al. 2015). The Penn World Table publishes different GDP series (see Feenstra et al. 2015). This paper uses a measure where the levels of GDP have been constructed based on multiple PPP benchmark years and therefore correct for changing prices between these benchmarks. Feenstra et al. (2015) argue that this measure offers the best cross-country and time-series comparisons of real GDP.[4]

Employment is measured in terms of persons engaged and therefore includes both employees and self-employed. Human capital is an index based on the average years of schooling and an assumed rate of return to education around the world.

An index of capital was constructed based on the Penn World Tables and the Total Economy Database (Conference Board 2017). The capital index was constructed using a capital stock benchmark for the base year 2011 and then multiplying with the yearly growth rates of total capital services.

Data on mobile broadband penetration was retrieved from the GSMA Wireless Intelligence Database (GSMA 2018) and is available for the years 2002–2014. The data consists of the mobile broadband connections expressed as a percentage of total connections. Mobile broadband connections represent SIM cards registered on the mobile network in a device capable of download speeds of 256 kb/s or greater, including 3G (eg WCDMA and HSPA) and 4G (eg LTE, WiMAX) network technologies.

The difference between connections and subscribers is that one subscriber can have multiple connections. Moreover, the penetration rate in each country before the introduction of mobile broadband is denoted as missing values in the GSMA database, but the real meaning of these missing values is that they are too small to be recorded. Thus, we replace the initial missing value with number zero. The data quality might differ between different countries. A few

[4] An alternative method to estimate GDP across countries and time is to use one PPP benchmark year and then project backward and forward in time by using national accounts data. This method has been criticized by Johnson et al. (2013), showing that estimates vary substantially across different versions of the Penn World Tables with greater variability the farther the estimate is from the benchmark year. In section 7, we test the robustness of our results based on the alternative method of measuring GDP across countries and time.

countries have very different diffusion patterns of mobile broadband penetration such as Cambodia. Possible reasons might be government policies such as subsidies etc. However, in general, there is no shared pattern of occurrence of deviation.

As discussed below, in order to deal with simultaneity issues by means of instrumental variable, we use data on fixed Internet users per 100 inhabitants and mobile cellular telephone subscriptions per 100 inhabitants in the year 2002 (see section 6). Data for these indicators in 2002 are based on the World Telecommunication/ICT Indicators database (International Telecommunication Union 2015). Moreover, we also use data on fixed broadband subscriptions per 100 inhabitants to test the robustness of our results.

Table 1 OECD and non–OECD countries included in our regression

OECD countries	Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Japan, Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovakia, South Korea, Spain, Sweden, Switzerland, United Kingdom
Non–OECD countries	Albania, Angola, Argentina, Armenia, Bahrain, Bangladesh, Bolivia, Bulgaria, Burkina Faso, Cambodia, Cameroon, China, Colombia, Costa Rica, Côte d'Ivoire, Croatia, Cyprus, Dominican Republic, Ecuador, Ethiopia, Hong Kong, India, Indonesia, Iran, Iraq, Jordan, Kyrgyzstan, Madagascar, Malawi, Malaysia, Malta, Moldova, Morocco, Niger, Nigeria, Peru, Philippines, Qatar, , Russia, Saudi Arabia, Senegal, Singapore, South Africa, Sri Lanka, Syria, Taiwan, Tajikistan, Tanzania, Trinidad and Tobago, Tunisia, Uganda, Ukraine, United Arab Emirates, Venezuela, Vietnam, Yemen, Zambia, Zimbabwe
Non-OECD countries with missing data for capital, employment or human capital	Azerbaijan, Bahamas, Belarus, Belize, Benin, Bosnia and Herzegovina, Brunei Darussalam, Cabo Verde, Central African Republic, Chad, Congo, Djibouti, Dominica, El Salvador, Equatorial Guinea, Fiji, Gabon, Georgia, Grenada, Guinea, Haiti, Honduras, Lao People's DR, Lebanon, Lesotho, Macao, Maldives, Mauritania, Mauritius, Mongolia, Namibia, Nepal, Nicaragua, Oman, Panama, Paraguay, Rwanda, Sao Tome and Principe, Seychelles, Saint Kitts and Nevis, Saint Vincent and the Grenadines, Suriname, Swaziland, Togo, Uzbekistan

In total data for 135 countries are used in our regressions. Countries with GDP data missing for any of the investigated years or data on our instrumental variables i.e. mobile-cellular subscriptions per 100 inhabitants and fixed Internet subscriptions per 100 inhabitants were dropped.[5] Data for capital, employment and human capital is missing for 45 countries and these countries are therefore excluded once we include these variables in our model.

[5] This implies that the US was excluded due to missing data for fixed Internet subscriptions per 100 inhabitants.

Table 1 shows a list of the countries that were included divided into OECD and non-OECD countries.

Table 2 shows descriptive statistics of the variables used throughout the analysis. It shows that both GDP and capital vary considerably between countries. Already in 2002, mobile phone subscriptions per 100 inhabitants had reached 110 (in Taiwan). Moreover, the maximum value of mobile broadband penetration (as a percent of total connections) is 99 (for South Korea).

Table 2 Descriptive statistics

Variable	Mean	St. Dev.	Min	Max	No. obs
GDP based on multiple benchmark years (in PPP adjusted 2011 US$, millions)	434687	1228532	309	17100000	1755
GDP based on one benchmark years and national accounts growth rates (in PPP adjusted 2011 US$, millions)	456777	1254163	336	17200000	1755
Capital (in 2011 US$, millions)	2213597	5088327	26109	68500000	1248
Number of persons engaged (in millions)	18	79	0.04	798	1716
Human capital index	3	0.7	1	4	1495
Human capital index based on Mincerian approach	15797	80829	21	2003818	975
Mobile broadband connections (as a percent of total connections)	12	20	0	99	2054
Mobile broadband connections (as per 100 inhabitants)	14	27	0	294	2054
Mobile phone subscriptions in 2002 (as per 100 inhabitants)	28	30	0.1	110	2054
Fixed Internet subscribers in 2002 (as per 100 inhabitants)	6	10	0.004	49	2054
Fixed broadband subscriptions (as per 100 inhabitants)	9	11	0	47	1810
Bank credit to bank deposits (in percent)	99	67	9	880	1779
Patent applications (total)	14632	64863	1	928177	1161
Total trade (in constant 2010 US$, millions)	213715	445897	0	3804310	1730
Index of political stability and no violence	0.005	1	–3	2	1987

Note: The descriptive statistics include the full sample for each variable.

5. Results and discussion

A fixed effects (FE) model controls for or partials out the effects of the country specific components. An alternative to the fixed effects model is the random effects (RE) model which is used when variation across countries is assumed to be random and not correlated with the dependent and independent variables in the model. Based on a Hausman test we reject the hypothesis that the random effects model is most appropriate and instead conclude that the fixed effects model is most appropriate.[6]

Table 3 Regressions investigating the economic impact of mobile broadband

	Dependent variable: log of GDP					
	Pooled regression		Fixed effects		Fixed effects	
Mobile broadband introduction (1%)	2.06*** (0.273)		0.07*** (0.022)		0.07*** (0.021)	
Mobile broadband introduction (5%)		1.96*** (0.276)		0.03 (0.025)		0.002 (0.027)
Log of labor (ln*L*)					0.71*** (0.168)	0.71*** (0.174)
Log of capital (ln*K*)					0.19 (0.128)	0.20 (0.128)
Log of human capital (ln*HK*)					0.76 (0.508)	0.77 (0.528)
Constant	10.78*** (0.176)	10.78*** (0.176)	10.78*** (0.024)	10.78*** (0.024)	7.38*** (1.375)	7.14*** (1.383)
Country fixed effects	No	No	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.14	0.14	0.66	0.66	0.76	0.76
Number of observations	1755	1755	1755	1755	1170	1170

Note: The estimates are based on pooled OLS and fixed effects. Cluster robust standard errors are presented in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively.

Table 3 shows the results for the introduction of mobile broadband for countries with no missing values for either mobile broadband or GDP. The results show that there is a positive and significant association between the introduction of mobile broadband at a 1 percent level based on both OLS and fixed effects regressions. There is a quite a large difference between the estimated mobile broadband coefficient based on pooled and fixed specifications, respectively. This implies that there are other country specific effects. Thus, it is likely that our OLS estimates for the pooled specification are biased.

At the threshold of 1 percent, the result implies that after a country has introduced mobile broadband, GDP level is on average 7 percent higher than before its introduction..[7] At the

[6] The Hausman test for the fixed and random effects model including time specific effect gives a statistic of 97.92 with a *Prob>chi2* = 0.0000. Thus, we reject the hypothesis that the random effects model is most appropriate and instead conclude that the fixed effects model is most appropriate.

[7] Our results are also robust if we run our regressions based on the assumption that mobile broadband is introduced when the ratio is larger than 0%. We find that the coefficient is larger (0.09 compared to 0.07 when we control for capital and labor) and still significant at the 1% level.

threshold of 5 percent the coefficients are insignificant once controlling for country fixed effects and additional inputs of capital and labor. Thus, there is evidence of an “introduction effect” from mobile broadband. That is to say, it would appear the effect on the level of GDP is confined to the initial years of adoption, when broadband has been adopted by only a very small fraction of the population. One possible explanation could be that this effect is driven by large initial investments when mobile broadband is first rolled out, which in turn affects GDP.

Table 4 Regressions investigating the economic impact of mobile broadband

	Dependent variable: log GDP					
	Pooled regression		Fixed effects		Fixed effects	
Log of mobile broadband penetration (as percent of total connections) (*lnMB*)	0.05 (0.062)	0.05 (0.047)	0.05*** (0.005)	0.06*** (0.005)	0.03*** (0.005)	0.03*** (0.006)
Years since mobile broadband introduction (1%)	0.151*** (0.034)		0.021*** (0.004)		0.007 (0.004)	
Years since mobile broadband introduction (5%)		0.185*** (0.037)		0.015*** (0.003)		0.0006 (0.003)
Log of labor (ln*L*)					0.51*** (0.146)	0.49*** (0.135)
Log of capital (ln*K*)					0.34** (0.131)	0.38*** (0.121)
Log of human capital (ln*HK*)					–0.01 (0.399)	0.17 (0.426)
Constant	11.22*** (0.177)	11.30*** (0.175)	11.61*** (0.010)	11.62*** (0.009)	6.73*** (1.437)	6.08*** (1.256)
Country fixed effects	No	No	Yes	Yes	Yes	Yes
Year dummies	No	No	No	No	No	No
R^2	0.07	0.08	0.58	0.56	0.71	0.71
Number of observations	1060	1060	1060	1060	800	800

Note: The estimates are based on pooled OLS and fixed effects. Cluster robust standard errors are presented in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively.

Table 4 shows the association between the continuous mobile broadband variable and logGDP. The coefficient is insignificant based on pooled OLS estimation, but becomes significant once country fixed effects are introduced into the model. Moreover, the coefficient remains highly significant when we include labor, human capital and capital in the regression and control for the number of years since mobile broadband was introduced at the threshold of one and five percent.

Table 5 shows the estimated regression based on first differences. Mobile broadband penetration is positive and significant at the 5 percent level. The results imply that on average a 10 percentage points increase in the growth of mobile penetration is associated with a 0.1 percentage points increase in GDP growth. This is an important association given that 0.1 percent of world GDP accounted for approximately 76 billion US dollars in 2016 (World Bank 2017). Labor and capital are still positive and highly significant.

Table 5 Regressions investigating the economic impact of mobile broadband

	Dependent variable: Δln GDP		
	Fixed effects		
	First differences	Three years differences	Five years differences
ΔMobile broadband penetration (Δ*lnMB*)	0.01** (0.005)	0.03*** (0.007)	0.04*** (0.008)
ΔLabor (Δln*L*)	0.53*** (0.103)	0.56*** (0.147)	0.55*** (0.173)
ΔCapital (Δln*K*)	0.35*** (0.100)	0.30*** (0.123)	0.27* (0.145)
ΔHuman capital (Δln*HK*)	−0.36 (0.417)	−0.58 (0.446)	−0.11 (0.450)
Constant	−0.02 (0.015)	−0.02 (0.017)	−0.02 (0.015)
Year dummies	Yes	Yes	Yes
R^2	0.32	0.37	0.47
Number of observations	710	531	360

Note: The estimates are based on fixed effects. Cluster robust standard errors are presented in parenthesis. Long differences include n-period moving average of the growth rates of each variable. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively.

Once we introduce longer differences based on 3-years and 5-years moving averages of the growth rates, we find that the change in mobile broadband penetration is associated with larger changes in lnGDP. Brynjolfsson and Hitt (2003) found that the returns of computers increased when long term differences were introduced. These findings were based on firm level data and the suggested interpretation was that the observed contribution of computerization would be accompanied by relatively large and time consuming investments in complementary inputs, notably organizational capital. Since similar results are found for mobile penetration, one hypothesis is that the effects from mobile broadband are also tied to investments in other intangibles such as training and organizational capital (the other is that longer differences result in less measurement error).

6. Instrumental variable approach

6.1 Simultaneity

The methods used thus far have determined a correlation rather than a causal effect of mobile broadband introduction and penetration on GDP growth.

One way of addressing simultaneity is by using instruments that are correlated with the explanatory variable but not with the error term. Some of the instruments proposed from earlier studies are tax credit for ICT investment and specific types of housing (Abramovsky and Griffith 2006; Dettling 2013). However, none of these instruments are available across countries.

In this article, identification of instruments relies on the nature of mobile broadband. Mobile broadband networks are designed for accessing the Internet on mobile phones or computers anywhere and at any time. Thus, the number of mobile broadband connections is closely related to the number of mobile phone subscribers and computer users. Prior to the introduction of mobile broadband in many countries, the penetration of computers had most probably already reached a saturation point among individuals belonging to the labor force and construction of mobile phone infrastructure had been completed in many countries.[8] However, consumption upgrade leads consumers to replacing cellphones with smartphones and desktop computers with new generation of laptops and tablets.

Mobile broadband networks (primarily 3G and 4G) were constructed along the existing base stations for mobile telephony by upgrading or modifying the pre-existing cellular infrastructure. This implies that a country with better 2G cellular network is likely to have a higher adoption rate of mobile broadband. Thus, the pre-determined adoption rate of computers and mobile phones can effectively predict the diffusion trajectory of mobile broadband. Therefore, it is possible to model the maximum penetration of mobile broadband as a linear function of the diffusion of mobile phone infrastructure and personal computers before the diffusion of mobile broadband:

$$\gamma_i = \theta_0 + \theta_1 MobilePhone_{i0} + \theta_2 Internet_{i0} \tag{6}$$

[8] A survey carried out by Eurostat (2018) in 15 EU-countries suggests that the share of individuals that had never used a computer decreased from 31 percent in 2005 to 14 percent in 2014 among all individuals. However, the same survey suggests that corresponding figures (available from 2009) for the group aged 25-64 who are employees, self-employed or family workers are considerably lower.

where γ_i is the maximum penetration level in country *i*. $MobilePhone_{i,0}$ is mobile phone penetration, measured as mobile-cellular telephone subscriptions per 100 inhabitants in 2002 and $Internet_{i,0}$ is the diffusion of computers proxied by fixed Internet subscribers per 100 inhabitants in 2002. Both indicators are gathered from the International Telecommunication Union (2015).

The model used is based on a logistic form of S-shaped diffusion curve that was first introduced in economic analysis by Griliches (1957) and is also applied by Czernich et al. (2011) to analyze the economic impact of fixed broadband. It suggests that the diffusion of new technology follow an S-shaped curve and approaches its maximum penetration level eventually, which is best described through a logistic curve of the following form:

$$MobileBroadband_{it} = \frac{\gamma_i}{1+exp[-\beta(t-\tau)]} + \varepsilon_t \qquad (7)$$

where $MobileBroadband_{it}$ is mobile broadband penetration rated in country *i* at year *t*. γ_i is the same as in equation (6) i.e. a country-specific and time-invariant parameter that determines the maximum penetration of mobile broadband when *t* approximates infinity. Both β and τ are invariable across countries and determine the diffusion speed and the inflection point of the diffusion process, respectively. At the inflection point τ, the diffusion curve has its maximum growth rate $\beta/2$. ε_t is the error term. By substituting γ_i in equation (7) with equation (6), we obtain a non-linear first stage model, which we estimate and so predict broadband penetration for all country-years.

One critique of our identification strategy is that it rests on the assumption that the 2002 level of mobile and Internet penetration do not have any impact on the subsequent levels of GDP. However, there is a vast literature on General Purpose Technology suggesting the economic impact from different technologies are realized with a lag (David 1990; Helpman 1998). Thus in the first stage, we did not use all years of cell phone penetration and fixed Internet penetration rates. Instead only cell phone and fixed Internet data in 2002 were used in the non-linear model to predict the mobile broadband introduction dummy and penetration rate as an approximation to the true diffusion process (from 2002–2014). Thus, any direct impact of cell phone or fixed Internet on GDP is unlikely to confound the results in the second stage.

Moreover, since mobile broadband would be expected to be a substitute for both mobile phones and fixed Internet we would expect the economic impact from these to decrease rapidly as the diffusion of mobile broadband takes off.

Our identification strategy rests on the assumption that the 2002 level of mobile and Internet penetration do not have any impact on subsequent GDP, controlling for other factors. Recall that in the first stage, we use only cell phone and fixed Internet data in 2002 to predict the mobile broadband introduction dummy and penetration rate. In the second stage, we use fixed effects and hence control for any unobserved correlation between the level of GDP and initial mobile penetration.

6.2 First stage results

The first stage least squares model is estimated based on non-linear least squares. *Table 6* shows the results of the full sample.

Table 6 Technology diffusion curve (first stage of the instrumental variable model)

	Dependent variable: Mobile broadband penetration rate		
	Non-linear least squares		
	Model 1	Model 2	Model 3
Cell phone penetration rate in 2002	0.93*** (0.060)		0.67*** (0.050)
Fixed Internet penetration rate in 2002		2.63*** (0.253)	0.93*** (0.130)
Diffusion speed (β)	0.49*** (0.036)	0.49*** (0.043)	0.49*** (0.035)
Inflection point (τ)	2010.2*** (0.347)	2010.3*** (0.456)	2010.2*** (0.325)
Constant (θ)	11.07*** (1.098)	22.32*** (1.971)	12.38*** (1.128)
R^2	0.83	0.78	0.84
Number of observations	1755	1755	1755

Note: Non-linear least squares estimation. Robust standard errors are presented in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. In model 3 we have run the F-test and can reject the hypothesis that our instruments are jointly equal to 0 at the 1% significance level.

The coefficients for cell phone and fixed Internet penetration in 2002 remain significant at the 1 percent level for all models. Thus, pre-determined cell phone penetration and fixed Internet usage have positive effects on the saturation level γ_i in the mobile diffusion curve. The inflection point is determined to be around 2010 which is in line with the actual diffusion process. In total, the estimated model provides a very good fit of the broadband diffusion process across countries.

Figures 1–3 plot the actual and fitted values of broadband penetration rate over time for the 135 different countries categorized as OECD countries, non-OECD countries and non-OECD countries with missing data on either capital, labor or human capital. Almost all countries exhibit a logistic curve of mobile broadband diffusion. For most countries the fitted line for mobile broadband diffusion tracks the actual line closely. In a few countries such as Japan, Macao and South Korea, there is a clear divergence of the predicted values from the actual trajectory. In general, there is no shared pattern of the occurrence of deviation, which implies that the first-stage model is not biased towards any specific direction. Hence, it is likely to be a reflection of heterogeneity across countries.

Figure 1 Actual and predicted mobile broadband diffusion in OECD countries

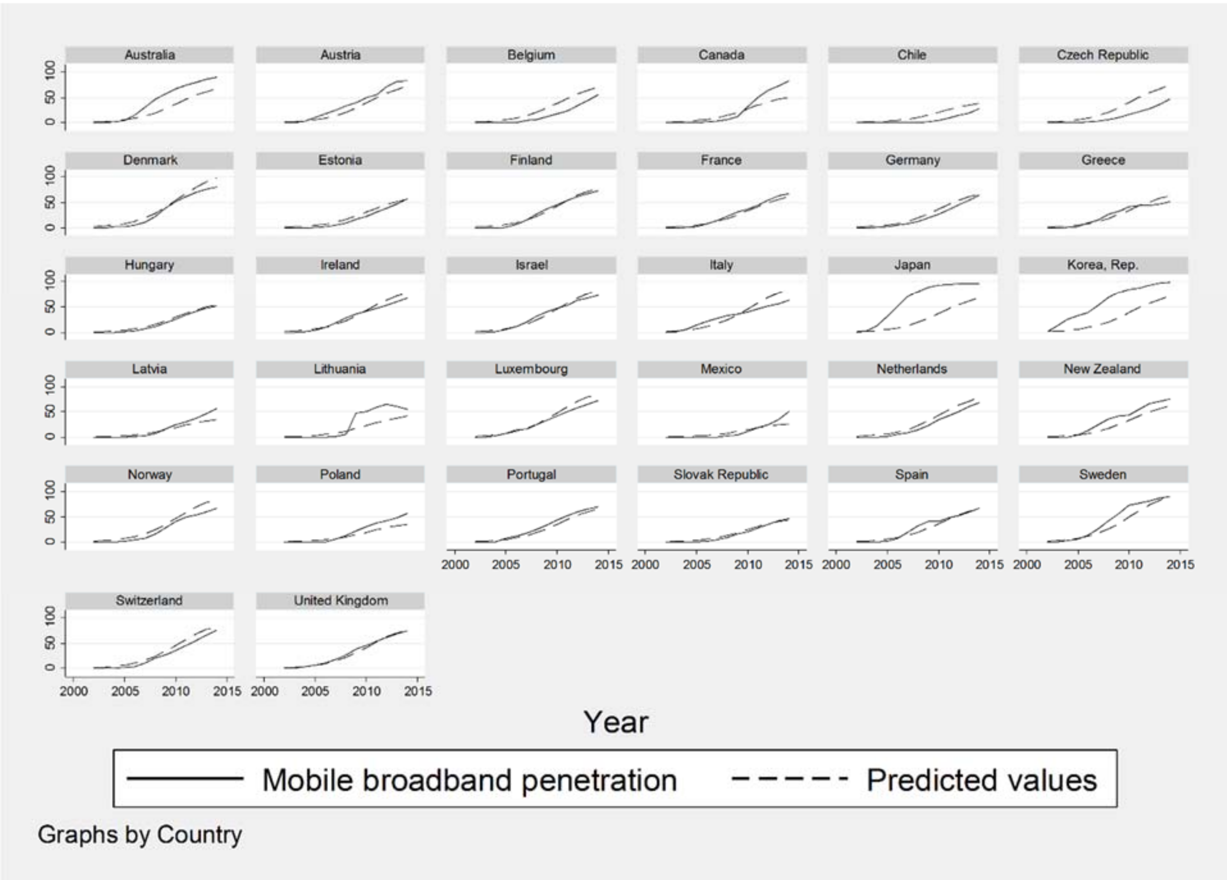


Figure 2 Actual and predicted mobile broadband diffusion in non-OECD countries

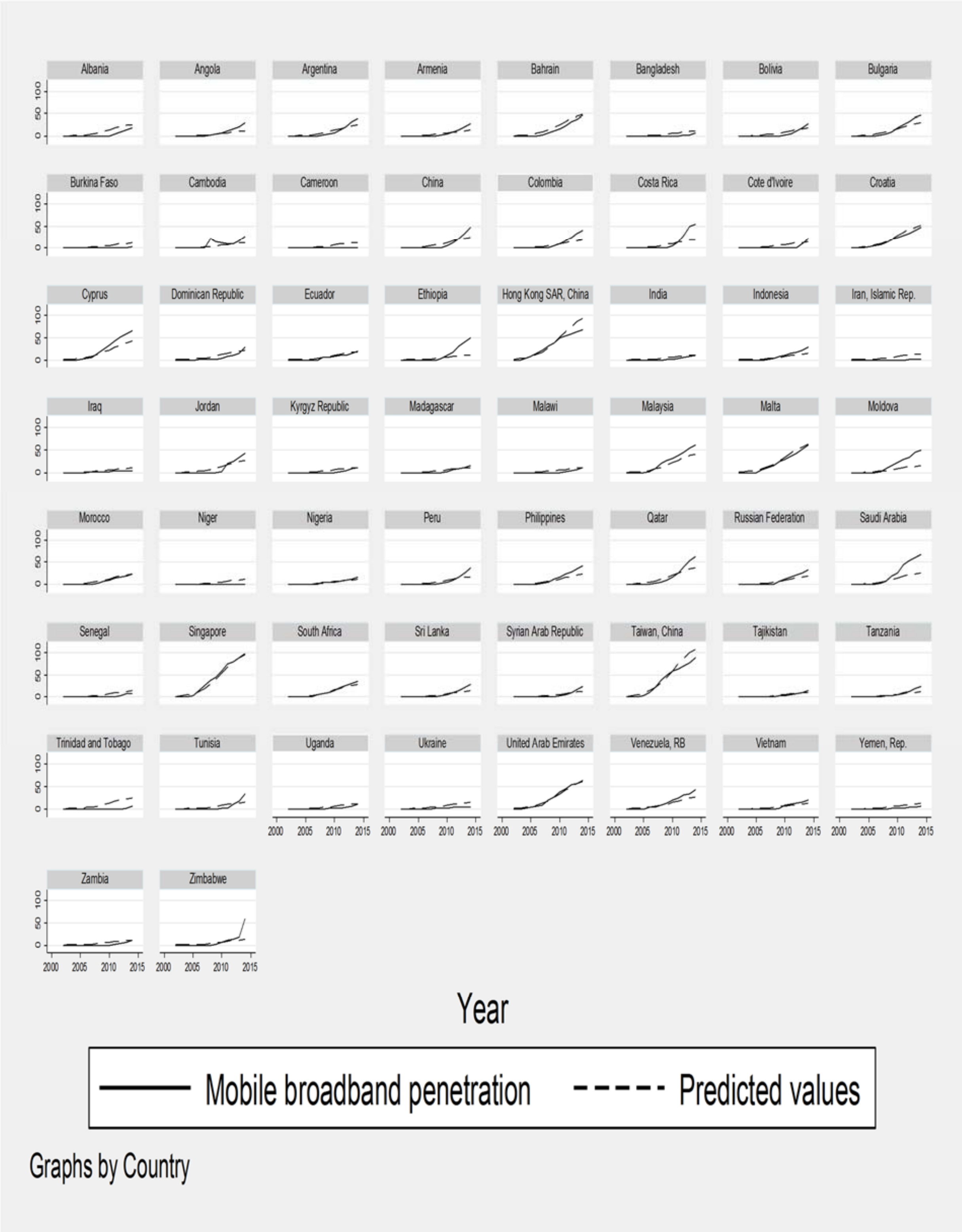
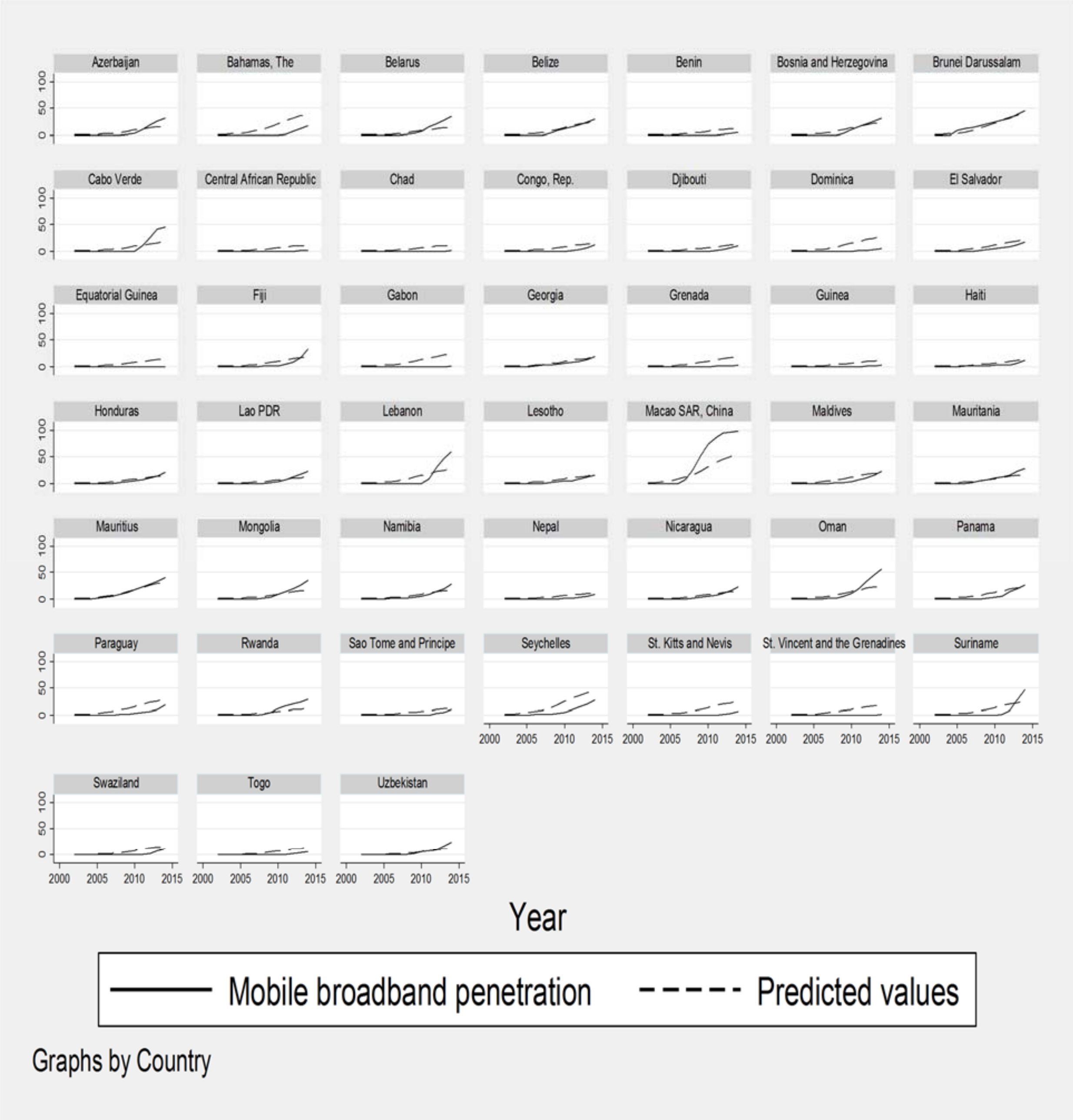


Figure 3 **Actual and predicted mobile broadband diffusion in non-OECD countries with missing data on either capital labor or human capital**



6.3 Second stage results

The first stage estimation predicted the diffusion process of mobile broadband based on cell phone and fixed Internet penetration levels in 2002. The second stage uses the fitted values of mobile broadband penetration rate and the predicted years of introduction based on the first stage regression in order to estimate the causal effect of mobile broadband on GDP. Standard errors in the second stage are bootstrapped (500 repetitions) since the independent variable was predicted by the first-stage estimation.[9]

Table 7 The effect of mobile broadband on log GDP (second stage of the instrumental variable model)

	Dependent variable: log GDP				
	Fixed effects				
Log of predicted mobile broadband penetration (as percent of total connections) (*lnMB*)	0.08*** (0.015)	0.12*** (0.024)	0.11*** (0.016)		
Lag of predicted mobile broadband penetration (*lnMB*) (t–1)				0.14*** (0.025)	
Lag of predicted mobile broadband penetration (*lnMB*) (t–2)					0.14*** (0.024)
Years since mobile broadband introduction (1%)		–0.016* (0.008)			
Years since mobile broadband introduction (5%)			–0.021*** (0.006)		
Years since mobile broadband introduction (1%) (t–1)				–0.025*** (0.009)	
Years since mobile broadband introduction (1%) (t–2)					–0.031*** (0.009)
Log of labor (ln*L*)	0.71*** (0.195)	0.69*** (0.185)	0.68*** (0.176)	0.66*** (0.167)	0.61*** (0.168)
Log of capital (ln*K*)	0.21 (0.128)	0.23* (0.132)	0.22* (0.120)	0.21* (0.121)	0.22* (0.122)
Log of human capital (ln*HK*)	0.83 (0.507)	0.93 (0.571)	0.94** (0.478)	0.75 (0.481)	0.43 (0.447)
Constant	7.07*** (1.348)	6.73*** (1.379)	6.81*** (1.263)	7.20*** (1.253)	7.48*** (1.281)
Country fixed effects	Yes	Yes	Yes	Yes	Yes
Year dummies	No	No	No	No	No
R^2	0.75	0.76	0.77	0.76	0.75
Number of observations	1170	1170	1170	1080	990

Note: Fixed effects estimation. Bootstrapped standard errors in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively.

Table 7 presents results based on the predicted mobile broadband penetration rate. The results imply that mobile broadband penetration has a statistically significant positive effect on the level of GDP. Thus, a 10 percent increase in the mobile penetration rate causes (if the IV strategy identifies causal effects) the level of GDP to increase by 0.8 percent. The size of this

[9] Bootstrapping provides a way of estimating standard errors when no formula is otherwise available or when available formulas make inappropriate assumptions. It implies drawing N observations with replacement from the original sample data. Using the resampled dataset, it is possible to apply the estimator and collect the statistics. This process is repeated many times.

effect is substantial as 0.8 percent of world GDP accounted for approximately 600 billion US dollars in 2016 (World Bank 2017).

If we control for the number of years since mobile broadband was introduced, we find a significant positive effect from predicted mobile broadband penetration. However, the impact from “years since mobile broadband introduction” is negative. This implies that our results are supportive of an introduction effect of mobile broadband. First, the use of logs means as penetration rises, that the marginal impact on lnGDP falls. Second, the “years since mobile broadband introduction” variable is negative, suggesting the effect of mobile broadband fades away as more years pass since it’s introduction.

The median annual growth rate of mobile broadband penetration ratio in our sample of 90 countries are 75.8 percent. If we apply this growth rate in our model we will find that the effect for the introduction year is (0.116*75.8%)=8.8%, the effect one year after introduction would be (0.116*75.8%–0.016*100*1)=7.2%, two years after introduction (0.1*75.8%–0.016*100*2)=5.6%, etc. Thus, the positive economic effect would disappear 6 years after introduction.

The results also show that the one and two year lagged coefficients remain highly significant. Thus, there appear to be a lagged effect from mobile broadband introduction, but the lagged “years since introduction” is still negative and larger. Thus, the lagged effect will fade away at a faster rate as more years pass.

In order to test if our results remain robust while introducing a dynamic specification we introduced a lagged dependent variable. Including a lagged dependent variable creates a bias in the estimate of the coefficient of the lagged dependent variable (Nickell 1981) as well as the other included variables (the bias is inversely proportional to the length of the panel i.e fades away as the panel gets longer). Nevertheless, *Table 8* shows that our estimates are smaller but still highly significant while introducing a lagged dependent variable in our regressions.

Table 8 The effect of mobile broadband on log GDP (including lagged dependent variable)

	Dependent variable: log GDP				
	Fixed effects				
Log of lagged dependent variable (lnY) (t-1)	0.77*** (0.025)	0.77*** (0.025)	0.75*** (0.025)	0.76*** (0.024)	0.72*** (0.028)
Log of predicted mobile broadband penetration (as percent of total connections) ($lnMB$)	0.02*** (0.005)	0.04*** (0.009)	0.04*** (0.006)		
Lag of predicted mobile broadband penetration ($lnMB$) (t-1)				0.05*** (0.008)	
Lag of predicted mobile broadband penetration ($lnMB$) (t-2)					0.04*** (0.007)
Years since mobile broadband introduction (1%)		–0.008*** (0.003)			
Years since mobile broadband introduction (5%)			–0.009*** (0.002)		
Years since mobile broadband introduction (1%) (t–1)				–0.011*** (0.003)	
Years since mobile broadband introduction (1%) (t–2)					–0.010*** (0.002)
Log of labor (ln$L$)	0.13* (0.071)	0.12* (0.065)	0.13** (0.063)	0.13** (0.058)	0.12* (0.060)
Log of capital (ln$K$)	0.02 (0.047)	0.03 (0.047)	0.02 (0.046)	0.03 (0.047)	0.06 (0.044)
Log of human capital (lnHK)	–0.02 (0.183)	0.04 (0.198)	0.04 (0.183)	0.03 (0.190)	–0.13 (0.195)
Constant	2.36*** (0.494)	2.21*** (0.507)	2.37*** (0.464)	2.35*** (0.485)	2.48*** (0.488)
Country fixed effects	Yes	Yes	Yes	Yes	Yes
Year dummies	No	No	No	No	No
R^2	0.92	0.92	0.92	0.92	0.90
Number of observations	1080	1080	1080	1080	990

Note: Fixed effects estimation. Bootstrapped standard errors in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively.

7. Robustness

This section tests the robustness of our results based on different country groups and additional data.

7.1 Different country groups

The countries in our sample are very different in terms of economic development. It could be argued that it is more appropriate to compare countries that are at similar stage in their economic development. In order to test the robustness among different country groups, we divide the countries into two groups based on the level of income in each country. The countries are classified based on GNI per capita provided by World Bank (2018). We define low-income countries as countries with an average income less than 4 125 US $ in 2014 and high-income countries with an average income above 4125 US $.

Table 9 The effect of mobile broadband on log GDP (second stage of the instrumental variable model)

	Dependent variable: log GDP					
	Countries with an income below US $ 4 125			**Countries with an income above US $ 4 125**		
Log of predicted mobile broadband penetration (as percent of total connections) (*lnMB*)	0.16*** (0.025)	0.18*** (0.040)	0.17*** (0.022)	0.06*** (0.019)	0.10*** (0.019)	0.09*** (0.021)
Years since mobile broadband introduction (1%)		–0.009 (0.019)			–0.02*** (0.006)	
Years since mobile broadband introduction (5%)			–0.01 (0.017)			–0.02*** (0.005)
Log of labor (ln*L*)	–0.05 (0.349)	–0.07 (0.336)	–0.05 (0.340)	0.79*** (0.239)	0.76*** (0.236)	0.75*** (0.240)
Log of capital (ln*K*)	0.22 (0.165)	0.23 (0.161)	0.23 (0.155)	0.22 (0.217)	0.26 (0.232)	0.26 (0.223)
Log of human capital (ln*HK*)	0.51 (0.952)	0.57 (0.988)	0.53 (0.919)	0.72 (0.573)	0.83 (0.606)	0.86 (0.558)
Constant	8.06*** (1.369)	8.01*** (1.369)	8.03*** (1.330)	7.21*** (2.524)	6.67*** (2.749)	6.56*** (2.596)
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	No	No	No	No	No	No
R^2	0.76	0.76	0.76	0.79	0.79	0.80
Number of observations	390	390	390	780	780	780

Note: Fixed effects estimation. Bootstrapped standard errors in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively.

According to *Table 9*, the results remain robust for both groups of countries based on income. The continuous effect from mobile broadband penetration remains highly robust for both income group. All coefficients are positive and highly significant at the 1% level. In general, the coefficients are considerably higher for low-income countries. For example once we do not control for the years since mobile broadband was introduced the coefficient for mobile broadband penetration is 0.16 for low-income countries compared to 0.06 for high-income countries. Moreover, the effect from years since mobile broadband introduction is insignificant for low income countries, while it is significant for high income countries.

In addition, we also test our regressions for OECD and non-OECD countries. According to *Table 10* the impact from mobile broadband is 0.02 for OECD countries and significant at the

10 percent level. However, when we control for a faster diffusion in countries that introduce mobile broadband later the mobile broadband coefficient for OECD countries becomes insignificant when introduction is defined as 1% penetration. For non-OECD countries the mobile broadband coefficients are highly significant and considerably larger than for the OECD countries.

Table 10 The effect of mobile broadband on log GDP (second stage of the instrumental variable model)

	Dependent variable: log GDP					
	OECD countries			Non-OECD countries		
Log of predicted mobile broadband penetration (as percent of total connections) (*lnMB*)	0.02* (0.012)	0.005 (0.012)	0.02* (0.010)	0.12*** (0.018)	0.14*** (0.024)	0.14*** (0.019)
Years since mobile broadband introduction (1%)		0.008 (0.005)			–0.01 (0.010)	
Years since mobile broadband introduction (5%)			0.003 (0.004)			–0.02** (0.009)
Log of labor (ln*L*)	0.22 (0.188)	0.24 (0.188)	0.23 (0.193)	0.61*** (0.205)	0.62*** (0.205)	0.63*** (0.213)
Log of capital (ln*K*)	0.62*** (0.146)	0.59*** (0.155)	0.61*** (0.152)	0.13 (0.129)	0.15 (0.131)	0.14 (0.128)
Log of human capital (ln*HK*)	0.14 (0.580)	–0.06 (0.707)	0.05 (0.721)	0.22 (0.551)	0.31 (0.586)	0.37 (0.578)
Constant	3.46* (1.796)	4.04* (2.013)	3.69** (1.903)	8.51*** (1.331)	8.25*** (1.347)	8.20*** (1.323)
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	No	No	No	No	No	No
R^2	0.83	0.83	0.83	0.78	0.79	0.79
Number of observations	403	403	403	767	767	767

Note: Fixed effects estimation. Bootstrapped standard errors in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. The following OECD countries have been excluded due to missing data: Iceland, Slovenia, Turkey and the United States.

The differences between OECD and non-OECD countries clearly highlight the economic relevance of our results. Chinn and Fairlie (2007) pointed out the digital divide across countries in terms of computer and Internet penetration. A comparison of our significant results suggests that a 10 percent increase in the mobile broadband penetration causes a 0.2 and 1.2 percent GDP increase in OECD and non-OECD countries, respectively. Thus, our results suggest that non-OECD countries on average could leapfrog by investing in mobile broadband and eventually catch up in economic development with OECD countries.

7.2 Testing robustness with additional data

As discussed in section 4, the Penn World Table publishes different GDP series. The regressions in this paper is based on GDP with multiple PPP benchmark years. Feenstra et al. (2015) argue that this measure offers the best cross-country and time-series comparisons of real GDP. Nevertheless, the Penn World Table also publishes an alternative measure of GDP based on PPP benchmark only for the year 2011 and then projected backward and forward in time by using national accounts data.

Table 11 The effect of mobile broadband on log GDP based on one benchmark year and national accounts growth rates (second stage of the instrumental variable model)

	Dependent variable: log GDP				
	Fixed effects				
Log of predicted mobile broadband penetration (as percent of total connections) (*lnMB*)	0.04*** (0.011)	0.08*** (0.011)	0.07*** (0.010)		
Lag of predicted mobile broadband penetration (*lnMB*) (t-1)				0.08*** (0.011)	
Lag of predicted mobile broadband penetration (*lnMB*) (t-2)					0.08*** (0.012)
Years since mobile broadband introduction (1%)		–0.017*** (0.004)			
Years since mobile broadband introduction (5%)			–0.019*** (0.002)		
Years since mobile broadband introduction (1%) (t–1)				–0.022*** (0.004)	–0.024*** (0.003)
Years since mobile broadband introduction (1%) (t–2)					
Log of labor (ln*L*)	0.38*** (0.125)	0.36*** (0.113)	0.35*** (0.104)	0.38*** (0.114)	0.38*** (0.113)
Log of capital (ln*K*)	0.29*** (0.089)	0.31*** (0.087)	0.31*** (0.080)	0.31*** (0.091)	0.33*** (0.096)
Log of human capital (ln*HK*)	0.38 (0.407)	0.48 (0.382)	0.47 (0.378)	0.45 (0.379)	0.34 (0.414)
Constant	7.13*** (1.001)	6.77*** (1.001)	6.90*** (0.897)	6.84*** (1.022)	6.76*** (1.051)
Country fixed effects	Yes	Yes	Yes	Yes	Yes
Year dummies	No	No	No	No	No
R^2	0.80	0.81	0.82	0.80	0.78
Number of observations	1170	1170	1170	1080	990

Note: Fixed effects estimation. Bootstrapped standard errors in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. GDP measurement is based on one benchmark year and national accounts growth rates instead of multiple benchmark years.

We test the robustness of our results by conducting similar regressions based on the GDP series with only one benchmark year. In general, the results are robust. *Table 11* shows the second stage results based on the predicted mobile broadband penetration rate and the alternative GDP series. The coefficients are generally smaller but still significant.

The mobile broadband introduction dummy and penetration rate predicted by the first stage estimation are both theoretical approximations to the true diffusion process. The first stage estimation confirms that the cell phone and fixed Internet coverage in 2002 places a limit on the maximum reach of mobile broadband. But the predicted mobile broadband penetration may also be correlated with the diffusion of fixed broadband. In order to control for this effect we also introduce a variable of fixed broadband, measured as subscribers per 100 inhabitants, into the regressions.[10]

Table 12 shows estimations of the impact from predicted mobile broadband penetration once we also control for actual fixed broadband penetration. Without controlling for the year since mobile broadband introduction, the coefficient of predicted mobile broadband penetration is 0.03 and significant at the 5% level. However, it becomes insignificant once we control for the number of years since mobile broadband introduction. One reason for this could be that we are not able to control for the years since fixed broadband was introduced. Moreover, the lagged coefficients are also significant, indicating that part of the effect on GDP from mobile broadband penetration comes with a lag.

[10] Data on fixed broadband subscribers per 100 inhabitants is based on the International Telecommunication Union (2015).

Table 12 The effect of mobile broadband on log GDP (second stage of the instrumental variable model)

	Dependent variable: log GDP				
	Fixed effects				
Log of predicted mobile broadband penetration (as percent of total connections) (*lnMB*)	0.03** (0.013)	0.007 (0.025)	0.04** (0.018)		
Lag of predicted mobile broadband penetration (*lnMB*) (t-1)				0.04 (0.024)	
Lag of predicted mobile broadband penetration (*lnMB*) (t-2)					0.06*** (0.022)
Years since mobile broadband introduction (1%)		0.009 (0.008)			
Years since mobile broadband introduction (5%)			–0.002 (0.005)		
Years since mobile broadband introduction (1%) (t–1)				–0.0005 (0.008)	
Years since mobile broadband introduction (1%) (t–2)					–0.009 (0.008)
Log of labor (ln*L*)	0.62*** (0.147)	0.63*** (0.163)	0.62*** (0.151)	0.60*** (0.148)	0.56*** (0.154)
Log of capital (ln*K*)	0.32*** (0.094)	0.31*** (0.098)	0.33*** (0.095)	0.30*** (0.096)	0.28*** (0.105)
Log of human capital (ln*HK*)	0.11 (0.441)	0.03 (0.478)	0.14 (0.440)	0.07 (0.463)	0.01 (0.466)
Log of fixed broadband penetration (*lnFB*)	0.05*** (0.009)	0.05*** (0.011)	0.05*** (0.011)	0.05*** (0.011)	0.05*** (0.012)
Constant	6.47*** (0.991)	6.73*** (1.068)	6.42*** (1.042)	6.90*** (1.047)	7.29*** (1.141)
Country fixed effects	Yes	Yes	Yes	Yes	Yes
Year dummies	No	No	No	No	No
R^2	0.81	0.81	0.81	0.80	0.78
Number of observations	1102	1102	1102	1033	957

Note: Fixed effects estimation. Bootstrapped standard errors in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively.

Finally, mobile broadband penetration is measured as the share of mobile connections in total connections. An alternative measure would be to relate mobile broadband to the population in each country. We find that our results are robust, once we measure mobile broadband penetration as mobile broadband connections per 100 inhabitants. *Table 13* shows the second stage results based on mobile connections per 100 inhabitants. The results show that a 10 percent increase in mobile connections per 100 inhabitants causes GDP to increase by 0.7 percent.

Table 13 The effect of alternative mobile broadband on log GDP (second stage of the instrumental variable model)

	Dependent variable: log GDP				
	Fixed effects				
Log of predicted mobile broadband penetration (connections per 100 inhabitants) (*lnMB*)	0.07*** (0.014)	0.11*** (0.022)	0.11*** (0.017)		
Lag of predicted mobile broadband penetration (*lnMB*) (t-1)				0.13*** (0.022)	
Lag of predicted mobile broadband penetration (*lnMB*) (t-2)					0.13*** (0.021)
Years since mobile broadband introduction (1%)		–0.018** (0.008)			
Years since mobile broadband introduction (5%)			–0.023*** (0.006)		
Years since mobile broadband introduction (1%) (t–1)				–0.026*** (0.008)	–0.031*** (0.008)
Years since mobile broadband introduction (1%) (t–2)					
Log of labor (ln*L*)	0.71*** (0.185)	0.69*** (0.173)	0.68*** (0.170)	0.66*** (0.178)	0.61*** (0.173)
Log of capital (ln*K*)	0.20 (0.132)	0.23* (0.123)	0.22* (0.122)	0.21* (0.122)	0.22* (0.116)
Log of human capital (ln*HK*)	0.82 (0.522)	0.90* (0.546)	0.88* (0.495)	0.70 (0.458)	0.36 (0.432)
Constant	7.11*** (1.394)	6.78*** (1.302)	6.93*** (1.280)	7.30*** (1.269)	7.60*** (1.205)
Country fixed effects	Yes	Yes	Yes	Yes	Yes
Year dummies	No	No	No	No	No
R^2	0.75	0.76	0.77	0.76	0.75
Number of observations	1170	1170	1170	1080	990

Note: Fixed effects estimation. Bootstrapped standard errors in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Mobile broadband penetration is measured as mobile broadband connections per 100 inhabitants instead of mobile broadband connections as a percentage share of total connections.

8. Conclusions

A number of different studies have shown that ICT is closely connected to macroeconomic development in terms of GDP. Most of these studies have focused on ICT as a whole or established technologies such as fixed telephone lines and computers. This paper investigates the effect of a much more novel technology, namely that of mobile broadband, on GDP.

Mobile broadband is measured as a percentage of total connections. Mobile broadband connections are defined as SIM cards registered on mobile network in a device capable of download speeds of 256 kb/s or greater, including 3G (e.g. WCDMA, HSPA) and 4G (e.g. LTE, WiMAX) networks technologies.

The paper first uses pooled and fixed effects estimation techniques to measure the impact of mobile broadband penetration. The results show that the introduction of mobile broadband is associated with increases in GDP. Possible explanations are the effect from early adopters, as well as large increased initial investments due to mobile broadband roll-out. Moreover, there is also a contemporaneous effect from mobile broadband. However, estimations based on moving averages find a larger effect based on a five-year differences compared to first differences. This is an indication that a lagged effect from mobile broadband penetration exists. One hypothesis is that complementary investments in intangibles are necessary before the full effect of mobile broadband networks can be realized.

A major concern when interpreting the results based on pooled and fixed effect models is that of simultaneity bias i.e. mobile broadband can be considered both a driver and a result of GDP growth. We address this potential bias with an instrumental variable (IV) approach. Mobile broadband networks were constructed along the existing base stations for mobile telephony by upgrading the pre-existing cellular infrastructure. Thus, it is possible to model the maximum penetration of mobile broadband as a linear function of the diffusion of mobile phone infrastructure and personal computers before the diffusion of mobile broadband (i.e. for the year 2002). By introducing a two stage model we are able to model mobile broadband penetration as a logistic form of S-shaped diffusion curve.[11]

Based on this two stage model, we find strong evidence that there is a statistically significant effect from mobile broadband on GDP both when mobile broadband is first introduced and gradually as mobile broadband diffuses throughout different economies. The results show that on average a 10 percent increase of mobile broadband adoption causes a 0.8 percent increase in GDP. Moreover, once we control for the years since mobile broadband was introduced, we find that the economic effect gradually decreases over time. For the country with median average growth of mobile broadband penetration, this implies that the economic effect have disappeared 6 years after introduction (if introduction is defined as a mobile penetration of 1 percent).

[11] The logistic form of S-shaped diffusion curve was first introduced in economic analysis by Griliches (1957) and is also applied by Czernich et al. (2011) to analyze the economic impact of fixed broadband.

The results are robust to alternative ways of measuring GDP and mobile broadband.Moreover, the results also show that the effect from mobile broadband is considerably larger and more significant in low income and non-OECD countries compared to high income and OECD countries. Thus, there is a considerable potential for low income and non-OECD countries to leapfrog by investing in mobile broadband infrastructure and eventually catch up in economic development with OECD countries.

Since 2001, global broadband connections have increased from approximately 27 thousand to 4.8 billion in 2017. Moreover, the use of data being sent via mobile networks has increased exponentially with approximately 65 percent on a year-on-year basis 2010–2015. Our results show that this extremely rapid diffusion of mobile broadband is driving positive macroeconomic development in terms of GDP.

9. References

Abramovsky, Laura and Griffith, Rachel (2006), “Outsourcing and Offshoring of Business Services: How Important is ICT?”, *Journal of the European Economic Association*, vol. 4, pp. 594–601.

Aghion, Philippe, Bloom, Nicholas, Blundell, Richard, Griffith, Rachel and Howitt, Peter (2005), “Competition and Innovation: An Inverted U Relationship”, *Quaterly Journal of Economics*, vol. 120, pp. 701–728.

Bloom, Nicholas, Draca, Mirco and Van Reenen, John (2016), “Trade Induced Technical Change: The Impact of Chinese Imports on Innovation, Diffusion and Productivity”, *Review of Economic Studies*, vol. 83, pp. 87–117.

Brynjolfsson, Erik, and Hitt, Lorin M. (2003), “Computing Productivity: Firm level Evidence”, *Review of Economics and Statistics*, vol. 85, pp. 793–808.

Chinn, Menzie D. and Fairlie, Robert W. (2007), “The Determinants of the Global Digital Divide: A Cross-Country Analysis of Computer and Internet Penetration”, *Oxford Economic Papers*, vol. 59, pp. 16–44.

Conference Board (2017), *Total Economy Database*, November, available online: www.conference-board.org/data/economydatabase

Corrado, Carol (2011), “Communication Capital, Metcalfe’s law, and U.S. Productivity Growth”, Economics Working Paper Series EPWP#11–01, Conference Board, New York.

Coyle, Diane and Williams, Howard (2011), “Overview”, *The Vodaphone Policy Paper Series*, no. 12, pp. 3–11.

Czernich, Nina, Falck, Oliver, Kretschmer, Tobias and Woessman, Ludger (2011), “Broadband infrastructure and economic growth”, *Economic Journal*, vol. 121, pp. 505–532.

Datta, Anusua and Agarwal, Submit (2004), “Telecommunications and economic growth: a panel data approach”, *Applied Economics*, vol. 36, pp. 1649–1654.

Dettling, Lisa J. (2013), Broadband in the Labor Market: The Impact of Residential High-Speed Internet on Married Women’s Labor Force Participation, Finance and Economics Discussion Series 2013–065. Federal Reserve Board, Washington D.C.

David, Paul (1990), “The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox”, *American Economic Review*, vol. 80, pp. 355–361.

Ericsson Mobility Report (2016), “Ericsson Mobility Report – On the Pulse of the Network Society”, Mobile World Congress, Ericsson, Stockholm.

Eurostat (2018), ICT usage in households and by individuals, available online: http://ec.europa.eu/eurostat/cache/metadata/de/isoc_i_esms.htm

Feenstra, Robert C., Inklaar, Robert and Timmer, Marcel P. (2015), “The Next Generation of the Penn World Table”, *American Economic Review*, vol. 105, pp. 3150 – 3182, available online: http://www.ggdc.net/pwt

Gerschenkron, Alexander (1952), “Economic Backwardness in Historical Perspective”, in: Hoselitz, Bert,F. (Ed.), *The progress of underdeveloped areas*, Chicago University Press, Chicago, pp. 3–29.

Goodridge, Peter, Haskel, Jonathan and Wallis, Gavin (2014), “The “C” in ICT: Communications Capital, Spillovers and UK Growth”, Discussion Paper 2014/10, Imperial College, London.

Griliches, Zvi (1957), “Hybrid Corn: An Exploration in the Economics of Technological Change”, *Econometrica*, vol. 25, pp. 501–522.

Gruber, Harald and Koutroumpis, Pantelis (2011), “Mobile telecommunications and the impact on economic development”, *Economic Policy*, vol. 26, pp. 387–426.

GSMA (2018), *GSMA Wireless Intelligence Database*, available online: www.gsmaintelligence.com

Hardy, Andrew P. (1980), “The role of the telephone in economic development”, *Telecommunications Policy*, vol. 4, pp. 278–286.

Helpman, Elhanan (1998), General Purpose Technologies and Economic Growth, in: Helpman, E. (Ed.), *Introduction*, MIT Press, Cambridge, MA.

International Telecommunication Union (2015), *World Telecommunication/ICT Indicators 2015 Database*, Geneva.

Jack, William and Suri, Tavneet (2014), “Risk Sharing and Transactions Costs: Evidence from Kenya’s Mobile Money Revolution”, *American Economic Review*, vol. 104, pp. 183–223.

Johnson, Simon, Larson, William, Papageoriou, Chris and Subramanian, Arvind (2013), “Is Newer Better? Penn World Table Revisions and Their Impact on Growth Estimates”, *Journal of Monetary Economics*, vol. 60, pp. 255–74.

Jorgenson, Dale, W., Mun S. Ho and Stiroh, Kevin J. (2008), “A Retrospective Look at the U.S. Productivity Resurgence”, *Journal of Economic Perspectives*, vol. 22, pp. 3–24.

Koutroumpis, Pantelis (2009), “The economic impact of broadband on growth: A simultaneous approach”, *Telecommunications Policy*, vol. 33, pp. 471–485

Nickell, Stephen (1981), “Biases in Dynamic Models with Fixed Effects”, *Econometrica*, vol. 49, pp. 1417–1426.

Nickell, Stephen (1996), “Competition and corporate performance”, *Journal of Political Economy*, vol. 104, pp. 724–746.

Oliner, Stephen D. and Sichel, Daniel (2000), “The Resurgence of Growth in the Late 1990s: Is Information Technology the Story?”, *Journal of Economic Perspectives*, vol. 14, pp. 3–22.

O’Mahony, Mary and Vecchi, Michela (2005), “Quantifying the Impact of ICT Capital on Output Growth: A Heterogeneous Dynamic Panel Approach”, *Economica*, vol. 72, pp. 615–633.

Qiang, Christine Zhen-Wei and Rossotto, Carlo M. (2009), “Economic Impacts of Broadband”, in: *Communications for Development 2009: Extending Reach and Increasing Impact*, pp. 35–50, World Bank, Washington D.C.

Rohman, Ibrahim and Bohlin, Erik (2012), “Does broadband speed really matter for driving economic growth? Investigating OECD countries”, *International Journal of Management and Network Economics*, vol. 2, pp. 336–356.

Röller, Lars-Hendrik, and Waverman, Leonard (2001), “Telecommunications Infrastructure and Economic Development: A Simultaneous Approach”, *American Economic Review*, vol. 91, pp. 909–923.

Solow, Robert M. (1987), “We’d Better Watch Out”, *New York Review of Books*, July 12, p. 36.

Sridhar, Kala S. and Sridhar, Varadharjan (2007), ”Telecommunications Infrasturcture and Economic Growth: Evidence from Developing Countries”, *Applied Econometrics and International Development*, vol 7, pp. 37–56.

Stork, Christoph, Calandro, Enrico and Gamage, Ranmalee (2014), “The future of broadband in Africa”, *info*, vol. 16, pp. 76–93.

Thompson, Herbert G. and Garbacz, Christopher (2007), “Mobile, fixed-line and Internet service effect on global productive efficiency”, *Information Economics and Policy*, vol. 19, pp. 189–214.

van Ark, Bart, O’Mahony, Mary and Timmer, Marcel (2008), “The Productivity Gap between Europe and the United States: Trends and Causes”, *Journal of Economic Perspectives*, vol 22, pp. 25–44.

Waverman, Leonard, Meschi, Meloria and Fuss, Melvyn (2005), "The Impact of Telecoms on Economic Growth in Developing Countries", *The Vodaphone Policy Paper Series*, no. 2, pp. 10–24.

Williams, Chris, Solomon, Gabriel and Pepper, Robert (2012), "What is the impact of mobile telephony on economic growth – A report for the GSM Association", Deloitte LLD, London.

Wooldridge, Jeffrey M. (2009), *Introductory Economics: A Modern Approach*, South Western, Mason, OH.

World Bank (2017), "Gross Domestic Product 2016", December, available online: https://databank.worldbank.org/data/download/GDP.pdf

World Bank (2018), "World Bank GNI per capita Operational – Guidelines and Analytical Classifications", February, available online: https://datahelpdesk.worldbank.org/knowledgebase/articles/378834-how-does-the-world-bank-classify-countries