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**Conference Paper**

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# **The impact of mobile technology on economic growth: global insights from 2000-2017 developments**

Bahia, Calvin<sup>1</sup>; Castells, Pau<sup>2</sup>; Pedros, Xavier<sup>3</sup>

Working Paper (June 2019)

## **Abstract**

The last two decades have seen a lot research devoted to understanding the economic impact of telecoms infrastructure; however, the explosion of mobile technology, especially in the last decade, has received much less attention. This study addresses important evidence gaps by considering the impact of different mobile technologies on economic growth and also assessing whether mobile has an additive impact when fixed broadband is in place. Applying IV and DPD models, our results show that during the 2000-2017 period, a 10% increase in mobile penetration raises GDP per capita by 0.59-0.76%, over and above the impact of fixed broadband. Disentangling mobile's average impact, we find a 10% increase in 2G mobile connectivity increases GDP per capita by 0.37-0.81%, while mobile broadband generates an additional impact of 0.12-0.72%. Our analysis suggests the magnitude of returns on mobile infrastructure upgrades does not diminish: mobile technology's impact is statistically on par with that of fixed broadband, and mobile broadband's average impact is also aligned with that of 2G connectivity. Moreover, the analysis shows that mobile's impact increases with a country's skills and with labour and capital from the services and industry sector, meaning there are important complementarities with mobile as a general purpose technology.

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

*JEL Classification:* F62, O11, O33, O47

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## 1. Introduction

A significant body of empirical research has studied the economic impacts of telecommunications over the last two decades. The impact of fixed communications infrastructure has been covered extensively, mostly by looking at technology deployments until 2010. Both fixed voice and broadband have been extensively researched, with studies finding improvements in GDP, employment, firm productivity and regional development. Significant empirical contributions include Koutroumpis (2009), Czernich et al. (2011), Czernich (2014), Gruber et al. (2014), Arvin & Pradhan (2014), Atasoy (2013), McCoy et al. (2017).

However, the empirical literature analysing the impacts of mobile technology is more limited, particularly when it comes to evaluating the rollout of more recent network technologies. While some studies have considered the rollout of mobile connectivity until 2010, these mostly miss the recent acceleration in the use of mobile broadband, as a result of the launch of 3G and 4G networks worldwide (for instance, see Thompson & Garbacz 2011, Gruber & Koutroumpis 2011, Aker 2010, Forero 2013 or Muto & Yamano 2009). More recently, some papers have specifically addressed the impact of mobile broadband globally, providing some useful insights. For example, Edquist et al. (2017) find a 10% increase in mobile broadband adoption to cause 0.6-2.8 percent increase in economic growth, on average. Consistent with the latter, ITU (2018) finds a 10% increase in mobile broadband to drive a 1.8-2 percent increase in developing economies, with developed countries being less subject to these impacts.

With the latest evidence from Edquist et al. (2017) and ITU (2018), however, there still remain some gaps. Firstly, the incremental impacts of 2G mobile connectivity and mobile broadband (i.e. 3G and 4G) are not still well understood, globally and in the last decade. Moreover, there is also a gap in evaluating these impacts while controlling for fixed infrastructure.<sup>4</sup> Secondly, the mechanisms by which mobile connectivity and broadband drive economic growth are still largely unexplored. While some research has looked at the role of income (including ITU 2018), no global study over the recent periods has assessed the underlying interactions of mobile technology with other factors that can shift its impact, particularly skills and economic structure. Third, while ITU (2018) and Edquist et al. (2017) have proposed SEM and diffusion-based IV 2SLS methods to deal with the endogenous relationship between mobile technology and economic growth (drawing on similar approaches used in earlier studies), there are other robust methods that can be implemented, which can yield complementary insights.

This working paper aims to address these gaps, making a significant contribution to the existing body of empirical literature. First, we address the aggregate, macroeconomic impact of mobile technology, differentiating the effect of 2G mobile connectivity (i.e. basic 'voice/SMS' mobile) and mobile broadband (i.e. 3G and 4G). Our global panel, covering the period 2000 to 2017, allows us to analyse the rollout of mobile technology almost in its entirety. We also account for fixed broadband, in order to isolate mobile's additional impact over and above existing fixed-line infrastructure. Second, we look at some of the macroeconomic determinants of the impact of mobile - including skills and economic structure, which have been found to be important drivers of ICT impact in the broader literature. Finally, this paper is novel in leveraging both internal and external instruments in an IV and Dynamic Panel Model (DPD) setting, in order to account for endogeneity in both mobile technology and fixed broadband.

Our empirical strategy is two-fold. We start with an IV 2SLS framework, where we focus on instrumenting mobile technology, using mobile spectrum and market concentration as exogenous factors that are strongly linked to the degree of a country's infrastructure development. We then turn to a DPD model, where we apply the Arellano Bond estimators. This model allows us to add a partial adjustment mechanism, common in economic growth models, as well as to control for the impact of fixed broadband through the addition of internal instruments.<sup>5</sup> We primarily look at the impact of 2G mobile connectivity and mobile broadband, using data from GSMA Intelligence.

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<sup>4</sup> While ITU (2018) assesses the impact of both fixed and mobile broadband, this is done in analytically separated exercises.

<sup>5</sup> Unlike most other papers that apply a DPD model, we incorporate external as well as internal instruments (see Bertschek et al. (2017) for a comprehensive review).

Our findings can be summarized in three areas:

- First, our results show that a 10% increase in mobile penetration drives an raises GDP per capita between 0.59 to 0.76%, over and above fixed broadband's impact - depending on the model specification. Disentangling mobile's average impacts, we find a 10% increase in 2G connectivity to increase GDP per capita from 0.37 to 0.81%, and a 10% increase in mobile broadband to add impacts coefficients of the range from 0.12 to 0.72% - on top of fixed broadband.
- Secondly, we find that the magnitude of mobile's average impact is on par with what we find for fixed broadband, suggesting that mobile has a substantial effect on top of fixed broadband. Consistent with this, our IV results provide evidence that the scale of the impact of mobile broadband is similar to that of 2G mobile connectivity (i.e. coefficients are not statistically different).<sup>6</sup> These findings are against the idea that there could be diminishing returns across ICT infrastructure upgrades, and suggest powerful mobile-driven productivity and efficiency mechanisms.
- Third, our findings show that mobile's impact, as a general purpose technology, depends on its interaction with a country's skills and economic structure. Countries that have more a skilled population tend to benefit more from mobile, suggesting complementarities between human capital accumulation and mobile infrastructure. Economic structures that combine mobile technology along services and industry sectors also see higher gains, also suggesting complementarities in non-mobile capital and labour. We also find that that, on average, there are increasing returns to mobile adoption - or that the impact of mobile increases at higher levels of mobile penetration - likely due to both network and learning effects.

The rest of the paper is structured as follows. Section 2 gives a brief overview of the literature, summarizing the mechanics behind the impact of mobile technology and mobile broadband, as well as some relevant empirical insights from the mobile, broadband and ICT literature. Section 3 develops the IV 2SLS and DPD GMM methodology we implement, and Section 4 discusses the characteristics of our data. Section 5 presents the results of this working paper version, as of both the impact of mobile and some of the determinants of its impact. We then summarize our main findings and implications in Section 6.

## 2. Literature review

### 2.1 Theoretical remarks

Mobile infrastructure can drive economic growth through a number of mechanisms. Most obviously, investing in mobile infrastructure itself leads to greater output because it raises the demand for intermediate inputs. However, the economic returns to mobile infrastructure investment are much greater than these *direct* returns on investment, since the communications enabled by mobile technology drive well-acknowledged improvements in efficiency and productivity across the economy. Notably, the subsequent deployment of mobile infrastructure, over the past three technology waves (2G, 3G and 4G) has enabled a number of applications with relevant economic implications (Table 1).

Table 1. Characteristics of mobile technology cycles

	2G	3G	4G
<i>Illustrative cycle length</i>	1990–2006	2006–2011	2009–Present
<i>Services</i>	Primarily voice	Voice and data	Voice and fast data
<i>Applications</i>	Voice calls, SMS, MMS, browsing (limited)	High-speed browsing, applications	Video conferencing, mobile TV
<i>Band type</i>	Narrow band	Wide band	Ultra-wide band
<i>Speed</i>	14.4 kbps	3.1 Mbps	100 Mbps

<sup>6</sup> Note this is not confirmed in our DPD model estimates - which may require adjusting lag structures in light of diagnostic tests.

Efficiency and productivity gains enabled by these mobile services fundamentally happen by (i) reducing information, search and transaction costs; and by (ii) complementing or replacing existing production inputs.

Firstly, mobile infrastructure improves the functioning of marketplaces for goods, services, labour and capital. Specifically, it encourages economic activity by lowering search and information costs – enabling new transactions, which they did not exist before (*market creation effect*), or improving existing transactions, which can now be carried out in a cheaper, quicker and more convenient way (*efficiency effect*). As a result, goods and services markets benefit from more trade and competition; workers in the labour market have access to more job opportunities and firms to a wider talent pool; and capital markets see increased borrowing and lending activity.

Mobile infrastructure also directly enhances the productivity of an economy. This is because mobile infrastructure enables quicker, cheaper and more convenient processes of production – which improve the utilisation of labour and non-mobile capital (*productivity effect*). Some applications enabled by mobile infrastructure complement existing inputs, making them more productive – for instance, mobile technology applications allow firms to coordinate their labour more effectively or to use their capital in the most productive manner. Other applications enabled by mobile infrastructure replace part of labour or non-mobile capital, resulting in cost savings.

## 2.2 Insights from the empirical literature

The mobile and fixed broadband literature has generally found positive and statistically significant effects, although the magnitude of these vary across studies (see Table 2 below). Beyond these impact numbers, however, the broader empirical literature on fixed wireline and broadband, along with the few studies on mobile technology, provide some useful insights around some of the mechanisms underlying the economic impact of ICT infrastructure - which we review in this section.

Table 2. Selected economic impact estimates in the literature

Research area	Author	Main finding on macroeconomic growth
Mobile broadband	ITU (2018)	A 10% increase in mobile broadband to drive a 1.8-2 percent increase in developing economies, while impact is insignificant in developed countries
Mobile broadband	Edquist et al. (2017)	A 10% increase in mobile broadband causes a 0.28-2.8 percent increase in economic growth
Mobile	Gruber & Koutroumpis (2011)	A 10% increase in mobile penetration generates average growth returns of 0.2 percent in high income countries and 0.11 percent in low income economies
Fixed broadband	Czernich et al. (2011)	A 10 percentage point increase in broadband penetration drives annual growth per capita between 0.9 to 1.5 percentage points
Fixed broadband	Koutroumpis (2009)	A 10% increase in fixed broadband adoption generates a 0.23 percent increase in GDP growth

### *Macroeconomic determinants*

Countries with skilled labour are likely to realise greater impacts of telecommunications infrastructure, as this allows them to better absorb ICT capital. Giday (2019) found that mobile broadband in Sub-Saharan Africa has low impact in areas of low ICT skill of internet users. Similarly, pre-existing human capital increases broadband's impact on firm creation (McCoy et al. 2017) and wage growth (Forman et al. 2012; Atasoy 2013, Mack & Faggian, 2013). Also, regions that have thicker labour markets for complementary services, or those with more labour diversity, experience stronger impacts of broadband (Forman et al. 2012).

Across economic sectors, the literature suggests that telecoms as a general purpose technology can drive most substantial gains in services and industry, where there are more complementarities between capital and labour, and telecoms infrastructure. Fixed line/broadband studies have found service

sectors such as retail trade benefit the most (Cronin et al. 1993; Cieslik & Kanjewsk 2004), as well as finance, insurance and real estate (Greenstein & Spiller, 1995). More recently, the broadband literature shows stronger impacts in technology-intensive, scientific and technical sectors (Atasoy 2013; Kolko 2012; McCoy et al. 2017); in banking, trade, construction and health (Nadiri & Nandi 2018); or, in rural areas, the hospitality sector (Canzian et al. 2015).

Across countries, the literature also suggests that efficiency and productivity gains of mobile and broadband tend to be higher in countries with isolated regions and fragmented population - where the costs to engage in economic activity are high. For instance, mobile connectivity has been found to allow businesses access to markets in remote areas, and to significantly decrease price dispersion between distant markets with high transportation costs (Aker 2010; Muto & Yamano, 2009). Broadband is also a significant driver of employment and wage growth in isolated regions (Atasoy, 2013; Czernich, 2014; Whitacre et al. 2014). Broadband has also been found to increase the counts of both low and high-tech firms, local and foreign (McCoy et al. 2017).

#### *The returns to mobile technology and fixed infrastructure*

The literature suggests that countries with scarce fixed deployment benefit more from mobile telecommunications (Lee et al. 2012, ITU 2018). This is because the efficiency and productivity improvements discussed above partly overlap between fixed and mobile, and so countries with pre-existing fixed infrastructure should see less gains, as compared to economies where mobile connects the population to basic communications and broadband for the first time. Additionally, some studies have specifically addressed whether mobile and fixed telecoms' impacts are complementary or substitutive, with mixed results: some have found that mobile and fixed usage increases adoption in both directions (Ward & Zheng 2016), while others have found mobile connectivity to be a substitute for landlines (Waverman et al. 2005).

The literature also suggests that returns to mobile technology generally increase with greater adoption. This can be due to network effects - e.g., with more adoption, users have more people with whom to interact, creating new and better uses cases - and/or due to learning effects - e.g., with more time since adoption, population gains skills (Gruber & Koutroumpis 2011). Studies have reported several adoption thresholds from which economies earn a lot more from the same infrastructure stock - for basic mobile and fixed wireline, this has been found at 30-40% (Gruber & Koutroumpis 2011); for broadband, larger impacts are found earlier, at above 10-30% (Czernich et al. 2011; Gruber et al. 2014; Koutroumpis 2009). While these increasing returns findings are generalized, however, it has also been argued that gains could start diminishing after certain levels of *high* adoption are achieved - in an inverted-U fashion, due to a "market saturation effect" (ITU 2018).

A separate issue is the extent to which telecoms infrastructure upgrades (e.g., from fixed wireline, to fixed broadband, to mobile and mobile broadband) generate constant returns or whether these are non-linear - a question that has not deserved much empirical attention. Ahlfeldt et al. (2017) finds broadband speeds have diminishing returns, so that the economic impact is greater when starting from relatively slow connections, while Koutroumpis (2018) has found opposite results. For the rest, one can only compare estimates found in literature using different datasets and methods, so it is not possible to draw conclusions on the nature of returns across technology upgrades.

#### *The role of income*

The role of income would be, a priori, ambiguous, given some of the mechanisms discussed above clearly play in different directions. On the one hand, developing countries have labour and capital that tends to be less complementary with ICT infrastructure - given their education and economic structure, vis-à-vis more developed countries. On the other, developing countries have much limited fixed infrastructure deployment, meaning there is more room for mobile technology to drive productivity and efficiency gains - still not driven via fixed infrastructure. Some papers have empirically found that mobile broadband and mobile in general have larger impacts in low income countries (ITU 2018, Waverman et al. 2005), suggesting the mechanic of the lack of fixed infrastructure dominates over the lack of complementary labour and capital. However, there is some evidence suggesting the opposite - Gruber & Koutroumpis (2011) find mobile adoption to drive twice the returns of low-income markets.

### 3. Methodology

This paper addresses the macroeconomic impact of mobile technology from 2000 to 2017, differentiating the effect of 2G mobile connectivity (i.e., basic ‘voice/SMS’ services) from mobile broadband (i.e. 3G and 4G), while controlling for the rollout of fixed broadband.

The primary challenge to address in studying the impact of mobile infrastructure on GDP is the endogenous relationship between GDP and a country’s mobile technology endowment. This is due to the inherent circularity between growth and infrastructure development. The existing broader telecoms literature has addressed this primarily in three ways: Instrumental Variables (e.g., Czernich et al. 2011); Structural Equations Models (e.g., Gruber et al. 2014); and through dynamic panel data models (e.g., Arvin & Pradhan, 2014). In the most recent mobile broadband literature, ITU (2018) has made use of SEM techniques to exogenize mobile technology, while Edquist et al. (2017) has used an IV approach using a diffusion curve approach for the first stage.

In this paper we propose a framework where we use both internal and external instruments, in order to account for the endogeneity of mobile technology, and of fixed broadband. First, we start with an Instrumental Variable 2SLS framework, using mobile spectrum and market concentration as exogenous factors that are strongly linked to the degree of a country’s mobile infrastructure development.<sup>7</sup> We are not aware of recent research on mobile technology that has leveraged these instruments.<sup>8</sup> We then turn to a DPD model, where we apply the Arellano Bond estimator. This model includes a lagged dependent variable, allowing for a partial adjustment mechanism in GDP, as well as to control for the impact of fixed broadband through the addition of internal instruments. The use a DPD framework is novel in the most immediate mobile technology wave of research, and the combination of both internal *and* external instruments is also novel in the more broader literature too.<sup>9</sup>

We start drawing on a Cobb-Douglas growth framework, which features decreasing marginal products, constant output elasticity and returns to scale. In this aggregate production function, we insert telecoms infrastructure. The output per capita of country  $i$  at time  $t$  depends on its human capital accumulation (which we measure as the average number of schooling years,  $SchoolingYears_{it}$ ); its stock of non-telecoms physical capital (as total investment,  $Investment_{it}$ ); its mobile physical capital (as the penetration of mobile technology  $G$ ,  $Mobile_{it}^G$ ) and of fixed broadband ( $FixedBB_{it}$ ). The terms  $\mu_i$ ,  $\theta_t$  are parameters for country and time fixed effects. Equation 1 below becomes our **OLS FE estimator**.

$$(Eq. 1) \quad \log(GDPcap_{it}) = \gamma_0 + \gamma_1 \log(SchoolingYears_{it}) + \gamma_2 \log(Investment_{it}) + \gamma_3 \log(Mobile_{it}^G) + \gamma_4 \log(FixedBB_{it}) + \mu_i + \theta_t + \epsilon_{it}^1$$

Disentangling the impacts of the  $Mobile_{it}^G$  variables (including of 2G, 3G and 4G technologies) is a challenging task due to multicollinearity. As the timeline of roll-out of these technologies partly overlaps (particularly for 2G and 3G), including them simultaneously could create bias to the technology-specific impacts we aim to address. The change on the type of service and their economic impact is also not linear between mobile technology generations. To address and simplify the empirical assessment, we simplify technology generations into (i) 2G mobile connectivity (i.e., voice and SMS); and (ii) mobile broadband, provided over 3G and 4G networks.

Acknowledging that both  $Mobile_{it}^G$  and  $FixedBB_{it}$  are endogenous to economic growth, after the OLS FE estimation we turn to an **IV estimation** where the focus is on instrumenting mobile technology. We build a Two-Stage Least Squares (2SLS) regression, where the penetration of mobile technology  $G$  in

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<sup>7</sup> Here we exclude the role of fixed broadband given we only have two external instruments in each first stage, and note some of our growth models will include multiple mobile technology variables.

<sup>8</sup> From the most recent literature on mobile, Edquist et al. (2017) estimated a diffusion curve using the penetration of mobile phones and computers as external instruments. From the more broader research, market concentration was used in Gruber et al. (2011), to address mobile technology developments pre-2007.

<sup>9</sup> For example, Arvin and Pradhan (2014) implements a DPD with internal instruments, and uses Granger causality tests to draw conclusions on the direction of impacts.

each country and year ( $\widehat{Mobile}_{it}^G$ ) is given by the predicted values resulting from a first stage. We use the spectrum holdings and market concentration specific to each technology  $G$  as instruments.<sup>10</sup>

$$(Eq. 2) \text{ Second stage } \log(GDPcap_{it}) = \gamma_0 + \gamma_1 \log(SchoolingYears_{it}) + \gamma_2 \log(Investment_{it}) + \gamma_3 \log(\widehat{Mobile}_{it}^G) + \mu_i + \theta_t + \epsilon_{it}^1$$

$$(Eq. 3) \text{ First stage } \widehat{Mobile}_{it}^G = \delta_0 + \delta_1 \log(SchoolingYears_{it}) + \delta_2 \log(Investment_{it}) + \delta_3 Spectrum^G + \delta_4 HHI^G + \mu_i + \theta_t + \epsilon_{it}^1$$

Firstly, in order to launch mobile networks, operators need to be able to use radio frequencies over the airwaves (i.e. spectrum). Importantly, the amount of spectrum holdings impacts not only the availability of mobile services (e.g., the *coverage* of a given mobile network), but also the quality of these (for instance, data services speeds, or *capacity*). Through both availability and quality of mobile technology (e.g., impacting both the supply and demand of mobile services), the amount of spectrum assigned affects the extent of use of mobile technology, while this should be exogenous relative to GDP per capita.<sup>11</sup> Importantly, countries have assigned mobile spectrum for different mobile technologies at different points in time, giving substantial variation in the instrument.

Secondly, we use market concentration as an instrument for mobile technology penetration, similar to Gruber et al. (2011). Lower levels of market concentration are generally thought to give operators incentives to maintain prices close to costs and to innovate in their networks, in order to retain customers. This should drive shocks in both the demand and supply-side, driving greater diffusion of mobile technology - while not impacting GDP otherwise. We note that, while there is evidence suggesting that the relationship between concentration and market outcomes is non-linear (particularly on innovation, where several studies have found inverted-U's)<sup>12</sup>, most of the variation in concentration in our dataset is caused by liberalisation processes (whose positive impact, moving from very high concentration, is not contested).

One key advantage of the mobile spectrum and market concentration instruments is that we can calculate them specifically for the three mobile network technologies that we assess, i.e., 2G, 3G and 4G. On the one hand, it is possible to track the amount of spectrum that each country uses for these three technologies. On the other, we can compute market concentration of 2G, 3G and 4G, using the number of mobile connections of each operator in each of these technologies. Overall, this provides instruments that allow for better first-stage predictions, as opposed to variables that are not technology-specific.

Our IV 2SLS estimation has two disadvantages. Firstly the model is not dynamic, in that it lacks a partial adjustment mechanism that is commonly used in macroeconomic time series modelling. Secondly, the IV model does not incorporate the role of fixed broadband, as this could create an endogeneity problem - but its absence could also create a bias on our mobile estimates through collinearity (as growth in mobile could be partly collinear to fixed broadband). To deal with these two issues, we build a **DPD model**, applying an Arellano-Bond estimator. This includes the first lag of GDP per capita<sup>13</sup> and we then combine the external instruments of the IV 2SLS framework with internal instruments (using second lagged differences as instruments).<sup>14</sup> This allows us to instrument both mobile technology variables as well as fixed broadband penetration.

<sup>10</sup> We run the analysis on Stata, using the package *ivreg2*.

<sup>11</sup> Particularly across countries of similar development levels.

<sup>12</sup> See, for instance GSMA (2018), Houngebonon Jeanjean (2016), HSBC (2015).

<sup>13</sup> We explored the use of deeper lags (both in the model and for the internal instruments), but overall results did not change.

<sup>14</sup> We apply a difference GMM estimator. We also implemented a system GMM (where lagged differences are used as instruments as well as lagged levels), with broadly consistent results.



## 4. Data

The panel underlying our analysis covers 168 countries, developed and developing, from 2000 to 2017. This allows us to look at almost the entire rollout of mobile technology, including 2G, 3G and 4G, across a diverse range of economies - key trends and data sources are available in the Appendix.

Regarding mobile market data, we measure mobile technology as the number of mobile connections, as a share of total population - which we refer to as market penetration. This proxies the extent to which the stock of mobile technology is available in each country and year. We use GSMA Intelligence data on mobile connections, broken down by network technology. GSMA Intelligence provides comprehensive datasets with mobile connections data being mostly sourced from operators' annual reports. Mobile connections of a certain network technology, per operator, is also used to compute HHI instruments (e.g., we obtain one overall HHI per country, as well as separate HHIs per 2G, 3G and 4G).

For mobile spectrum, which we use as an instrument to exogenize mobile technology, we also rely on GSMA Intelligence data. We have tracked the amount of spectrum assigned to operators at different points in time, in all the frequency bands available for mobile use in each country. For each operator, we have matched frequency bands to 2G, 3G or 4G, depending on what is the technology of the networks that they launch in these bands, at each point in time. Taking all this into account, we were able to build a panel of spectrum per operator for 2G, 3G and 4G, throughout the timeline in the panel, which we collapsed at the country level.

## 5. Results

### 5.1 The impact of mobile

We start by analysing the effect of mobile technology on economic growth under the OLS framework with fixed effects per country and year. While this controls for the effect of a range of factors on economic growth as well as country and time specific effects, it does not address the potential endogeneity concern between telecoms infrastructure and growth - and hence should be read with caution. Controlling for pre-existing levels of fixed internet broadband adoption, we find that all mobile technology metrics area are significant drivers of additional GDP per capita across all metrics of mobile technology (Table 3).

On average, a one percent increase in the penetration of mobile technology drives an increase in GDP per capita of 0.06%, over and above fixed broadband's impact (Model 1, Table 3). We note this coefficient is of similar magnitude as of that found for fixed broadband penetration - more formally, at the 1% level of confidence, we cannot reject the hypothesis that the coefficient from mobile is the same magnitude to that of fixed broadband. This means that mobile technology drives, on average, a similar economic impact to that of fixed broadband.

Models 4 and 5 (Table 3) represent different ways to split the average impact of mobile technology, between 2G mobile connectivity and mobile broadband. Firstly, Model 4 separately reports coefficients for 2G mobile connectivity and mobile broadband. Secondly, Model 5 also reports the specific parameter for mobile broadband, while anything left in mobile technology in general (i.e. 2G/3G/4G) should be attributable to 2G mobile connectivity.<sup>15</sup> Having this in mind, 2G mobile connectivity has impact coefficients ranging from 0.04 to 0.08, while mobile broadband appears to drive additional impacts although of a lower magnitude, between 0.01 and 0.02.

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<sup>15</sup> Analytically, Models 4 and 5 should be equivalent (as already said, in Model 5, anything left in mobile technology in general should be attributed to 2G mobile connectivity, after having accounted for mobile broadband). However, differences in parameters could be driven by patterns of substitution across mobile connections. Note that, as mobile technology evolves, mobile connections counted as 2G become 3G, and, after that, 3G connections become 4G. For 2G, this means that, in our panel, countries first see 2G connections growth, to then see a decrease in 2G, as these are substituted. For the panel underlying Model 4, where we have 2G and 3G/4G separately, this means the impact of the 2G variable on economic growth could be confounded (as the parameter may relate 2G decreases to economic growth). In the case of the 3G to 4G mobile connections substitution, this should not pose a problem, as this is internalized in the sum of 3G and 4G technology that we use.

Table 3. OLS Fixed Effects estimator

	(1)	(2)	(3)	(4)	(5)
Log Pen. 2G/3G/4G	0.06** (0.03)				0.07** (0.03)
Log Pen 3G/4G		0.01** (0.00)		0.01** (0.00)	0.02** (0.00)
Log Pen 2G			0.08** (0.02)	0.04** (0.02)	
Log Pen fixed broadband	0.06** (0.01)	0.07** (0.01)	0.05** (0.01)	0.06** (0.01)	0.06** (0.01)
Log Schooling years	0.00 (0.19)	0.05 (0.19)	-0.20 (0.25)	-0.05 (0.19)	-0.08 (0.19)
Log Investment	0.05 (0.06)	0.09 (0.06)	-0.00 (0.06)	0.07 (0.06)	0.05 (0.06)
Country and time FE	Yes	Yes	Yes	Yes	Yes
Observations	2,509	2,509	1,641	2,509	2,509
Number of clusters	168	168	168	168	168
R squared	0.99	0.99	0.99	0.99	0.99

Cluster robust standard errors in parentheses (\*\*\*)  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

Panel data in model 3 is restricted to period of growth of 2G connections

Turning to the IV approach, where we deal with the endogeneity of mobile technology, Table 4 below shows first and second stages of the basic IV growth model. Here we ignore the role of fixed broadband, to avoid any endogeneity that this may introduce. This comes at the expense of a potential upward bias to our estimations, as mobile internet growth may be in part collinear to fixed broadband - as already discussed.

Second stage regressions point to an average impact of mobile technology of 0.076 (Model 1, Table 4). Our analysis to break this down (Models 4 and 5) gives 2G mobile connectivity impacts in line with this average effect (0.070 to 0.081), with mobile broadband adding economic impact parameters between 0.057 and 0.072. For both of these models, an F test on the equality of the basic mobile and mobile broadband coefficients indicate we cannot reject the null hypothesis that the coefficients are equal, at the 1% level. Therefore, our IV results do not support the hypothesis of diminishing economic returns to technology - on the contrary, they suggest that mobile broadband has an additional impact on par with that of basic mobile.

First stage results show the HHI is a significant driver for mobile penetration. Its negative impact is likely driven by the 2000-2017 panel being subject to liberalization processes in the 2000s, where much of the concentration variation happens. Spectrum holdings for mobile broadband has positive impacts. We note spectrum for 2G mobile connectivity has a statistically significant negative sign in Model 4, but this refers for the first stage of a mobile broadband, whereas Model 3 has an expected positive sign. The sum of all spectrum also has a negative sign in Model 5, which could be due to collinearity with spectrum for broadband. Overall, we find that the combination of both HHI and spectrum variables produces a set of instruments that generally passes the tests for endogeneity, weak identification, under and over-identification.<sup>16</sup> Additionally, we prefer the combination of spectrum and HHI variables, as opposed to using them individually, since this allows us to instrument multiple endogenous mobile variables.

Relative to the OLS FE framework, a priori, we would expect IV results to be reduced, given the circularity of the relationship between economic growth and mobile should create an upwards bias. We note that the mobile technology in general and 2G mobile connectivity seems to be of similar

<sup>16</sup> Our endogeneity test suggest that, at the 1% level, we cannot reject the hypothesis that endogenous regressors are in fact exogenous, with the exception of model 5 in Table 4. On underidentification, results indicate we can reject the null hypothesis that the model is underidentified. Additionally, instruments are strong in that weak identification F- Statistics are all above the 10% maximal IV size Stock-Yogo critical values. Throughout the IV2SLS results shown in this paper, note that the 10% maximal IV size in most models correspond to critical values equal to or greater than 20. Additionally, following overidentification tests (not shown in Table 4), we cannot reject the null hypothesis of instruments being not valid, at the 1% - with the exception of model 1.

Table 4. IV Estimator, without fixed broadband

	(1)		(2)		(3)		(4)			(5)		
	1st Stage	2nd Stage	1st Stage	2nd Stage	1st Stage	2nd Stage	1st Stage (3G/4G)	1st Stage (2G)	2nd Stage	1st Stage (3G/4G)	1st Stage (2G/3G/4G)	2nd Stage
<b>Instruments</b>												
Log Spectrum	-0.0104 (0.0111)									-0.128*** (0.0313)	-0.005 (0.017)	
Log HHI	-1.272*** (0.130)						0.190 (0.236)	-1.541*** (0.142)		0.257 (0.239)	-1.278*** (0.129)	
Log Spectrum 3G/4G			0.0233 (0.0215)				0.201*** (0.0231)	-0.010 (0.013)		0.243*** (0.0263)	-0.007 (0.015)	
Log HHI 3G/4G			-1.853*** (0.146)									
Log Spectrum 2G					0.0379*** (0.0120)		-0.106*** (0.0251)	-0.005 (0.013)				
Log HHI 2G					-1.255*** (0.112)							
<b>Telecoms infrastructure</b>												
Log Pen. 2G/3G/4G		0.0756*** (0.0226)										0.0808*** (0.0233)
Log Pen 3G/4G				0.0306*** (0.00940)					0.0717*** (0.0137)			0.0571*** (0.0138)
Log Pen 2G					0.0711*** (0.0259)				0.0698*** (0.0199)			
<b>Controls</b>												
Log Schooling years	4.065*** (0.409)	-0.351*** (0.127)	6.640*** (0.866)	0.457*** (0.103)	2.921*** (0.310)	-0.648*** (0.135)	1.009* (0.583)	0.679*** (0.093)	-0.508*** (0.149)	1.113* (0.584)	4.066*** (0.409)	-0.435*** (0.134)
Log Investment	0.585*** (0.0785)	0.127*** (0.0306)	0.411** (0.202)	0.160*** (0.0299)	0.432*** (0.0698)	0.0490 (0.0334)	0.265 (0.205)	5.495*** (0.430)	0.109*** (0.0327)	0.285 (0.205)	0.583*** (0.079)	0.112*** (0.0316)
Constant	-1.109 (1.490)	10.43*** (0.364)	-4.628* (2.503)	8.915*** (0.317)	1.607 (1.378)	11.36*** (0.388)	-14.28*** (2.816)	-2.171 (1.637)	11.49*** (0.455)	-15.01*** (2.838)	-1.048 (1.449)	11.20*** (0.430)
Country and time FE	Yes		Yes		Yes		Yes			Yes		
Observations	2,400		1,445		1,629		2,400			2,400		
Endogeneity test p-value (1)	0.409		0.0383		0.7261		0.0002			0.0252		
Underidentification test p-value (2)	0.000		0.000		0.000		0.000			0.000		
Weak identification F-Statistic (3)	47.94		81.14		62.58		26.91			28.30		

Robust standard errors in parentheses (\*\*\*)  $p < 0.01$ , (\*\*)  $p < 0.05$ , (\*)  $p < 0.1$ ). Note we our panel has an insufficient number of clusters to calculate a robust, full rank covariance matrix of moment conditions (meaning standard errors wouldn't allow us to correctly assess statistical significance). Note the panel in model 3 is restricted to the period of 2G growth.

(1) P-value of the endogeneity test (C statistic).  $H_0$  is that the endogenous regressors are in fact exogenous.

(2) P-value of the Kleibergen-Paap rk LM statistic.  $H_0$  is that the model is underidentified.

(3) Kleibergen-Paap Wald rk F-statistic for weak identification.

magnitude (relative to OLS FE, if one takes into account the magnitude standard errors), while we note more intense impacts for mobile broadband. This could be due to other confounding factors which play a role in the OLS estimation (e.g., beyond the circularity between mobile and growth), which include the fact that our IV estimation does not control fixed broadband.

We now turn to results of the DPD model, which includes a partial adjustment mechanism and controls for endogeneity of both mobile and fixed infrastructure (as already discussed, here the inclusion of fixed broadband is exogeneized as well, as a result of the combination of both internal and external instruments). Broadly, the direction and magnitude of results of the IV 2SLS model is confirmed, providing further reassurance of the main findings.

As expected, Table 5 shows that controlling for fixed internet tends to reduce the impacts associated to mobile technology that we find relative to models with mobile only.<sup>17</sup> Controlling for fixed broadband, mobile technology has an average additional impact of approximately 0.059 (Model 7) - we note this is close to the point estimate of 0.051 for fixed broadband, which again suggests impacts are on par. Breaking down mobile's impact, we find mobile 2G connectivity's effect to range between 0.037 and 0.054, with mobile broadband adding between 0.014 and 0.012 (Models 9 and 10). Testing the equality of estimates of basic mobile against mobile broadband, here we reject the null hypothesis that they are equal, at either the 5% or 1% level of confidence (this is true for all models where we combine both 2G mobile connectivity and mobile broadband in Table 5) - in contrast with our IV findings.

The fact that estimates decrease relative to IV 2SLS results is expected, given the DPD GMM controls for fixed broadband. However, we note that DPD GMM results are provisional and need to be taken with some caution, since some diagnostic tests indicate it needs further calibration. In particular the associated p-values for the AR(2) (which tests for autocorrelation) and Hansen's J statistic (which tests for over-identifying restrictions) suggests that the control variables and instruments may need to be reconfigured.

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<sup>17</sup> This suggests indeed that controlling for fixed infrastructure is important when studying the role of mobile technology, since their partly collinear developments likely induce a bias.

Table 5. DPD GMM Estimator (all sample)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Log GDP per capita t-1	0.720*** (0.0208)	0.348*** (0.0364)	0.711*** (0.0244)	0.667*** (0.0336)	0.572*** (0.0409)	0.547*** (0.0312)	0.324*** (0.0374)	0.534*** (0.0347)	0.457*** (0.0387)	0.434*** (0.0413)
<b>Telecoms infrastructure</b>										
Log Pen. 2G/3G/4G	0.0874*** (0.0115)				0.113*** (0.0157)	0.0592*** (0.0216)				0.0545** (0.0240)
Log Pen 3G/4G		0.0422*** (0.00470)		0.0114*** (0.00272)	0.0177*** (0.00291)		0.0404*** (0.00529)		0.0117*** (0.00318)	0.0138*** (0.00309)
Log Pen 2G			0.0920*** (0.0119)	0.0679*** (0.00834)				0.0663*** (0.0187)	0.0370*** (0.0112)	
Log Pen fixed broadband						0.0509*** (0.00794)	0.0143* (0.00865)	0.0475*** (0.00927)	0.0584*** (0.00690)	0.0555*** (0.00793)
<b>Controls</b>										
Log Schooling years	-0.163 (0.105)	-0.266* (0.146)	-0.0890 (0.134)	0.0811 (0.0999)	-0.576*** (0.140)	-0.113 (0.100)	-0.283* (0.146)	0.0767 (0.132)	-0.0940 (0.124)	-0.382*** (0.127)
Log Investment	0.128*** (0.0314)	0.168*** (0.0464)	0.123*** (0.0357)	0.116*** (0.0325)	0.127*** (0.0325)	0.176*** (0.0347)	0.198*** (0.0453)	0.177*** (0.0447)	0.167*** (0.0362)	0.181*** (0.0348)
Observations	2,137	1,314	1,371	2,137	2,137	1,885	1,287	1,122	1,885	1,885
Number of groups	135	130	135	135	135	134	129	134	134	134
Number of instruments	35	32	35	52	52	36	33	36	53	53
AR2 p-value (1)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hansen p-value (2)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Robust standard errors in parentheses (\*\*\*)  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ ). Note we our panel has an insufficient number of clusters to calculate a robust, full r covariance matrix of moment conditions (meaning standard errors wouldn't allow us to correctly assess statistical significance).

(1) Reports the p-value of the Arellano-Bond test for AR(2) in first differences. Null hypothesis is that there is no autocorrelation.

(2) Reports the p-value of the Hansen's J statistic. Null hypothesis is that the instruments as a group are exogenous.

## 5.2 Determinants of the impact of mobile

Replicating the DPD GMM framework on subsamples, we find some informative insights around the nature of the impact of basic mobile and mobile broadband - though again, these should be taken with caution given diagnostic tests suggest the model needs further calibration.

First, restricting the sample to the panel where secondary school enrolment is over 60%, most of our point estimates tend to increase (Models 1 to 5, Table 6) - note mobile technology's average impact increases to 0.113 from 0.087 in Table 5. This would suggest complementarities between human capital accumulation and mobile infrastructure or, in other words, that countries where labour is more skilled take more advantage of the use of mobile - consistent with what the broader ICT literature finds (for example, Foreman et al. 2012). We find these point estimates increases are less clear in subsamples based on basic education, which suggests the additional returns to mobile happen with higher education levels i.e. at least secondary school (this would be consistent with evidence of mobile adoption patterns).<sup>18</sup> Finally, we also note that these higher impacts happen to both 2G mobile connectivity and mobile broadband, which is also informative around both services enjoying complementarities with human capital.

Secondly, looking at the subsample where the share of employment of in industry and services is above 50%, we also find most point estimates to slightly increase (Models 6 to 10, Table 6): on average, mobile's impact increases to 0.091 from 0.087 in Table 5. The fact that we see, across models, impact coefficients increasing consistently, suggests that mobile technology does have greater impact in economies that have a capital and labour structure that complements better with the efficiency and productivity effects discussed in Section 2 (note our subsample essentially is excluding economies where the agriculture sector drives more than 50% of total employment). These findings on the role of economic structure are also overall consistent with results from the broader ICT literature - see, for example Kolko (2012).

Finally, our nonlinear model suggests that, on average, there are increasing returns to mobile technology (note the significant square term in Model 11, Table 6), or that countries at higher levels of mobile technology penetration enjoy stronger economic impacts. As suggested by the broader literature on telecommunications, this is likely to be caused by both network effects (e.g., productivity and efficiency-enhancing applications raising as more population is connected to mobile); and learning effects (e.g., time is required for mobile to adapt to labour skills and capital characteristics).

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<sup>18</sup> For instance, Gillwald et al. (2018) finds mobile adoption in Africa to be very limited at basic education levels.

Table 6. DPD GMM Estimator (subsamples and nonlinear model)

	Stronger education sample (a)					Industry and services sample (b)					Nonlinear
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Log GDP per capita t-1	0.493*** (0.0291)	0.323*** (0.0403)	0.513*** (0.0371)	0.403*** (0.0469)	0.319*** (0.0453)	0.453*** (0.0406)	0.293*** (0.0503)	0.490*** (0.0400)	0.257*** (0.0543)	0.176*** (0.0529)	0.517*** (0.0301)
<b>Telecoms infrastructure</b>											
Log Pen. 2G/3G/4G	0.113*** (0.0237)				0.135*** (0.0245)	0.0914*** (0.0286)				0.132*** (0.0321)	0.112*** (0.0271)
Log Pen 3G/4G		0.0391*** (0.00579)		0.0133*** (0.00410)	0.0197*** (0.00412)		0.0373*** (0.00740)		0.0228*** (0.00475)	0.0288*** (0.00435)	
Log Pen 2G			0.0948*** (0.0246)	0.0510*** (0.0140)				0.0467 (0.0319)	0.0497*** (0.0170)		
Log Pen. 2G/3G/4G ^2											0.00858*** (0.00242)
Log Pen fixed broadband	0.0443*** (0.0111)	0.0179 (0.0130)	0.0397*** (0.0127)	0.0583*** (0.00920)	0.0398*** (0.0110)	0.0601*** (0.0105)	0.0365** (0.0177)	0.0556*** (0.0109)	0.0608*** (0.0107)	0.0437*** (0.0120)	0.0478*** (0.00843)
<b>Controls</b>											
Log Schooling years	0.0415 (0.122)	-0.240 (0.161)	0.436** (0.190)	0.215* (0.121)	-0.331** (0.161)	0.204 (0.137)	-0.168 (0.187)	0.584*** (0.198)	0.335** (0.143)	-0.158 (0.190)	-0.181* (0.107)
Log Investment	0.200*** (0.0423)	0.224*** (0.0500)	0.206*** (0.0652)	0.192*** (0.0458)	0.194*** (0.0423)	0.332*** (0.0563)	0.330*** (0.0516)	0.413*** (0.0904)	0.339*** (0.0521)	0.334*** (0.0497)	0.167*** (0.0331)
Observations	1,580	1,138	854	1,580	1,580	1,021	749	547	1,021	1,021	1885
Number of groups	120	116	115	120	120	85	80	82	85	85	134
Number of instruments	36	33	36	53	53	36	33	34	53	53	52
AR2 p-value (1)	0.000	0.000	0.005	0.000	0.000	0.000	0.000	0.008	0.000	0.000	0.000
Hansen p-value (2)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.010	0.010	0.000

Robust standard errors in parentheses (\*\*\* p<0.01, \*\* p<0.05, \* p<0.1). Note we our panel has an insufficient number of clusters to calculate a robust, full rank covariance matrix of moment conditions (meaning standard errors wouldn't allow us to correctly assess statistical significance).

(1) Reports the p-value of the Arellano-Bond test for AR(2) in first differences. Null hypothesis is that there is no autocorrelation.

(2) Reports the p-value of the Hansen's J statistic. Null hypothesis is that the instruments as a group are exogenous.

(a) Sample includes the panel where secondary education is above 60% gross.

(b) Sample includes the panel where industry and services account for more than 50% of employment

## 6. Conclusions

The last two decades has seen much research devoted to understanding the aggregate economic impact of telecoms infrastructure. While fixed communications and broadband have been extensively researched, however, the literature on mobile technology is more limited. Most studies have addressed the rollout of mobile until 2010, which mostly ignores the recent explosion in the use of mobile broadband thanks to the launch of 3G and 4G networks worldwide. Only a recent wave of research has aimed at addressing the role of mobile broadband. However, there still remains a number of research gaps. These include assessing (i) the additional, separate impacts of different mobile technologies (2G, 3G and 4G); (ii) whether mobile has an additive impact when fixed broadband is in place; (iii) how mobile technology interacts with other factors that change the nature of its impact; (iv) and the development of alternative, solid approaches to deal with the endogeneity between infrastructure and economic growth.

This study addresses these gaps, applying Instrumental Variable (IV) and Dynamic Panel Data (DPD) frameworks, and combining both internal and external instruments to deal with the endogenous relationship of mobile technology and fixed broadband with economic output. Analysing a panel of 168 developing and developed countries, from 2000 to 2017 - which captures almost the entire rollout of mobile technology so far - our main findings can be summarized in three areas.

First, our estimates indicate that a 10% increase in mobile penetration results, on average, on an increase in GDP per capita between 0.59 to 0.76%, depending on the model specification. Breaking down this average impact, we find that a 10% increase in 2G mobile connectivity increases GDP per capita between 0.37 to 0.70%, and that a 10% increase in mobile broadband separately drives an additional increase in GDP per capita ranging from 0.12 to 0.72%. Importantly, our DPD GMM framework further suggests that mobile technology drives substantial economic impact on top of fixed broadband - implying that the mechanisms of productivity and efficiency gains triggered by mobile technology operate on top of the role of fixed infrastructure.

Secondly, our estimates suggest that returns across communications infrastructure upgrades have broadly constant returns. Comparing estimates from the same models, we find that the average impact of mobile technology is on par with that of fixed broadband. Moreover, our IV results suggest that the impact of mobile broadband is of similar magnitude relative to that of 2G mobile connectivity. These findings are against the hypothesis that improvements on communications infrastructure generate diminishing returns, and suggest that the impact channels of mobile technology and fixed broadband on economy performance are not necessarily substitutes.

Third, our analysis shows some additional insights on the ways by which mobile technology may drive the impacts summarized above. We find that our point estimates of the impact of mobile tend to increase consistently when looking at countries with a higher proportion of population that have received secondary education. We also find that our point estimates increase with countries whose economic structure relies relatively more on services and industry. All in all, our analysis suggest complementarities of mobile with skills, labour and capital from services and industry - which generate higher gains. This paper also finds that returns to mobile technology, on average, increase throughout its adoption - which likely indicate network and learning effects. These results are consistent with the findings in the broader ICT literature, and give relevant insights for policy makers on how to increase mobile technology's impact.

There are a number of areas of further research, on the basis of our analysis. Firstly, there would be value in distinguishing impacts between developed and developing countries, applying the same framework of 2G mobile connectivity, mobile and fixed broadband. This is important as there are likely different dynamics in the impacts of mobile and fixed infrastructure - as argued in ITU (2018), the lack of fixed infrastructure could play a substantial role, even if developing countries have less complementary skills, labour and capital (whose role is important in our findings). Second, our finding on mobile technology's impact increasing with adoption could be better refined, looking at specific critical thresholds where impacts particularly increase; and analysing whether these are different in 2G mobile connectivity and mobile broadband.



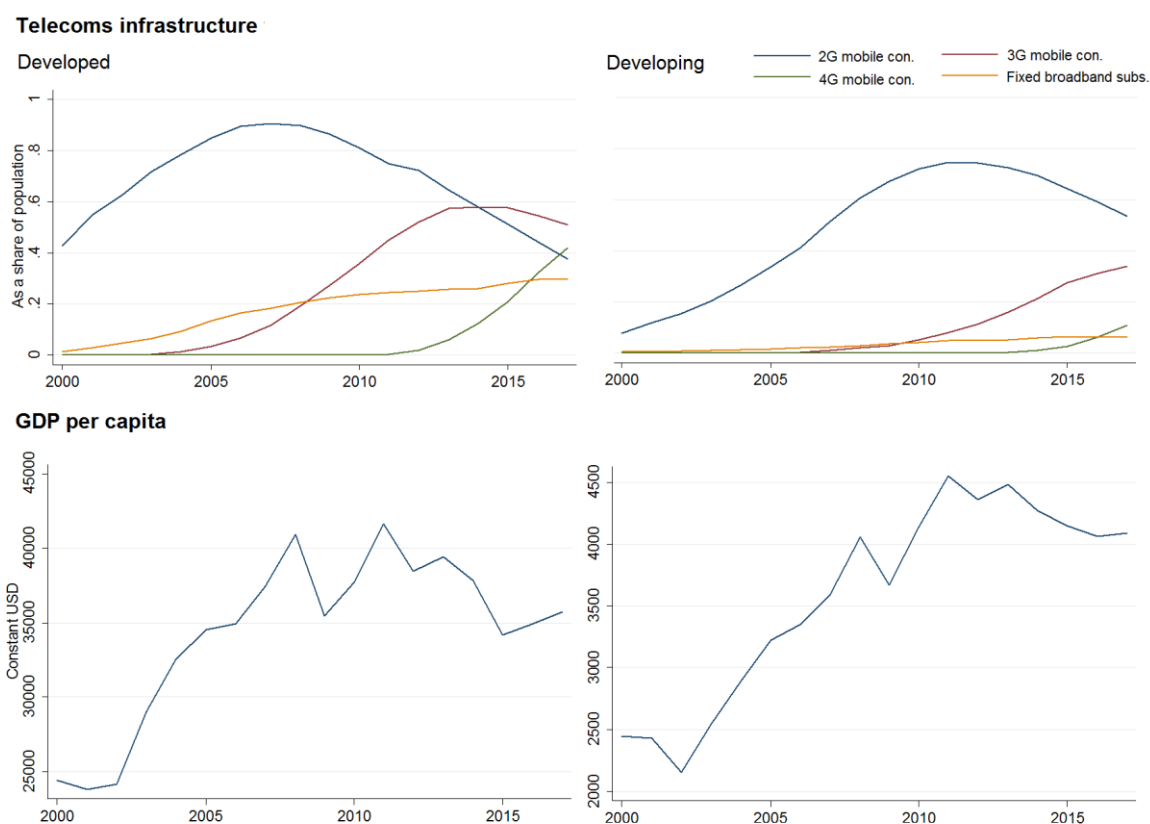
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## Appendix

Figure 1. Key telecoms infrastructure and GDP trends



In the legend, “con.” refers to connections, and “subs.” to subscribers.

Table 7. Data sources

Variable	Units and source
Penetration 2G	Connections/Population (GSMA Intelligence)
Penetration 3G	Connections/Population (GSMA Intelligence)
Penetration 4G	Connections/Population (GSMA Intelligence)
Penetration fixed broadband	Subscriptions per 100 habitants (ITU)
Spectrum, total	MHz (GSMA Intelligence)
Spectrum, 2G	MHz (GSMA Intelligence)
Spectrum, 3G	MHz (GSMA Intelligence)
Spectrum, 4G	MHz (GSMA Intelligence)
HHI, total	Based on connections (GSMA Intelligence)
HHI, 2G	Based on connections (GSMA Intelligence)
HHI, 3G	Based on connections (GSMA Intelligence)
HHI, 4G	Based on connections (GSMA Intelligence)
GDP per capita	Constant currency, USD bn, IMF
Schooling years	Average years of schooling (UN)
Investment	Total investment, as share of GDP (IMF)
Enrolment in secondary education	As share of students of all ages (WB)
Industry and services sector employment	As share of total employment (ILO)