Identifying Growth Effect of Internet Penetration *

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Abstract

This paper investigates the impact of broadband internet penetration on economic growth using China's city-level data during 2005 to 2019. The baseline OLS results from a structural model suggest that on average a 10% increase in broadband internet penetration growth is associated with a 0.4% increase in GDP per capita growth. A cost-benefit analysis translates this estimate into an average rate of return around 40% for investment in broadband internet infrastructure in China. To address the potential endogeneity, we exploit historical and topographical instrumental variables for broadband internet penetration for causal inference. Furthermore, utilizing the temporal and spatial variations from the Broadband China Pilot City Program, our staggered difference-in-differences analysis reveals innovation and entrepreneurship as two potential mechanisms underlying the growth effect of broadband internet penetration. Such mechanisms are consistent with the evidences that firms located in cities that participated in this program and especially at an earlier stage exhibit a notably higher level of digital adoption.

JEL Classification: O18, O47, E22, R53, H54

Key Words: Internet Penetration, Economic Growth, Broadband China Pilot City Program, Innovation, Entrepreneurship, Digital Adoption

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1 Introduction

Recent years have witnessed a stunning transformation of production systems and lifestyles arising from digitization, specifically, the high-speed broadband internet. New occupations including food delivery riders, Uber drivers, and influencers are created taking advantage of the fast development of broadband internet. Moreover, during this COVID-19 pandemic, people are getting familiar with contactless services and working from home, such as online education, e-commerce, and even telemedicine. This technological innovation eliminates spatial distance and facilitates digital transformation. Digitalization might be a powerful engine that fuels the growth of China, and it has already been an undergoing trial during China's current economic transformation. According to the Ministry of Industry and Information Technology (MIIT), the proportion of digital industry in China's GDP was 39.8% in 2021, and the annual growth rate of the digital industry was 16.2%, which was significantly higher than the GDP growth rate of 8.1%. The digital economy provides a strong impetus for sustainable and continuous economic development. However, with the advances in cutting-edge digital technology, including artificial intelligence (AI) that has achieved an equivalent or even superior level of performance compared to humans in various fields, challenges arise such as higher labor substitution (Acemoglu et al., 2022), modern productivity paradox (Brynjolfsson et al., 2017), resistance and difficulty in making additional complementary investments in intangible assets beforehand (Brynjolfsson et al., 2021), and intrusion on consumer privacy (Ichihashi, 2020). The impact of the internet is still a contentious arena for academic and political discourse.

Starting from the emergence of the internet in the United States, developed countries have attached high expectations to its beneficial effects, heavily investing in the deployment of broadband internet infrastructure (Greenstein and McDevitt, 2009; Czernich et al., 2011; Kolko, 2012). However, there is a burgeoning dispute among policymakers and researchers on the effects of broadband internet expansion on local economic outcomes. The growing literature on the macro-level effect of broadband usually suggests a positive association between broadband penetration rate and GDP growth, while the magnitude of this growth effect never reaches a consensus. Kolko (2012) estimates the 7-year growth effect of a 1% broadband expansion to be 0.06% by Ordinary Least Square (OLS) estimation and 0.64% by Instrumental Variable (IV) estimation over the period 1999-2006 throughout the United States. Czernich et al. (2011) suggest a 0.07% annual growth effect of broadband penetration rate by OLS and a 0.09% effect by two-stage least squares (2SLS) for 22 OECD countries during 1996-2007. A similar work by Koutroumpis (2009) finds a much lower effect: the elasticity is 0.025 using the panel of 22 OECD countries from 2002 to 2007. This strand of the literature only focuses on developed countries, nevertheless, the pattern in emerging countries may be different due to disparities in endowment, markets and institutions. In literature, there is a dearth of research focusing on the productivity effect of broadband internet in developing countries including China. Kumar et al. (2016) focuses on developing countries and conducts a time series analysis for the growth effect of internet subscriptions, broadband internet, mobile cellular, high-tech exports, and telephone fixed lines separately, without revealing any causal effect. A paucity of research in identifying the causality of broadband internet to economic growth in China indicates there is room for further study.

Given the intensive and extensive growth margins of internet penetration, what is the aggregate growth effect of broadband internet? Does the adoption of broadband internet boost economic growth? In literature, Acemoglu et al. (2022) discuss the labor market impact of AI. They find that although the AI-labor substitution and heterogeneous wage growth are visible at the micro-level, there is little aggregate effect of AI. Would the growth effect of broadband internet be neglectable at an aggregate level, just as indicated by the "modern productivity paradox" (Brynjolfsson et al., 2017; Benzell and Brynjolfsson, 2022)? Would developing countries enjoy a similar boosting effect as developed countries, as the developed countries have some favorable characteristics like higher institutional quality and more educated labor which are the complements to the broadband internet? Do the benefits of broadband internet exceed the costs so that the investment is efficient?

This paper estimates the growth effect of digital infrastructure, specifically, the broadband internet, based on a structural model derived from Mankiw et al. (1992) with data from prefecture-level cities in China during 2005-2019. The baseline OLS result suggests that a 10% increase in broadband internet penetration growth is associated with a 0.41% increase in annual GDP per capita growth. The instrumental variable method is utilized to mitigate the endogeneity problem. Results indicate that a 10% increase in broadband penetration growth leads to a 1.50-2.07% increase on average in GDP per capita growth. Exploiting the temporal and spatial variation provided by the Broadband China Pilot City Program, the staggered DID results further identify the intensive and extensive margins, which suggests the two mechanisms of the economically and statistically significant growth effect of broadband internet penetration: innovation and entrepreneurship. Finally, we uncover strong evidence that firms located in cities that participated in the program at an earlier stage exhibit notably higher levels of digital adoption. This phenomenon, in turn, underscores the pivotal role of city-level broadband internet infrastructure in facilitating and manifesting its impact on innovation, entrepreneurship, and overall economic growth. We also conduct a set of robustness checks, such as including year and city fixed effects, alternative measures of internet penetration, exclusion of internet nodal cites, and alternative choice of historical IV. The estimated rate of return to broadband internet infrastructure is 41.4% during the sample period, indicating a highly rewarding area that fuels the economic growth of China.

Our paper complements two strands of literature. First, this paper identifies the growth effect of digital infrastructure and addresses the reverse causality issue based on the structural model with endogenous technology growth. Second, our paper estimates the overall investment efficiency in digital infrastructure by comparing the aggregate benefit with the cost from the perspective of public infrastructure, which provides important policy implications to the infrastructure deployment for policymakers.

The remainder is organized as follows. Section 2 provides the institutional background of broadband internet deployment. Section 3 presents identification and data for estimating growth effect of broadband penetration. Section 4 presents empirical results. Section 5 investigates the mechanism using Broadband China Piolot City Program. Section 6 concludes the paper.

2 The broadband internet penetration in China

2.1 Institutional background

The internet is one of the most crucial infrastructures in the digital economy. The high-speed broadband internet has led to profound reforms in production and lifestyle, continuously reshaping economic development. China, as the fastest-growing economy, has realized the importance as well as the potential benefits of the internet and regarded the development of the internet as a major opportunity to advance reform and transformation. Therefore, great importance was attached to the deployment of broadband internet. Since being granted access to the Internet in 1994, China's broadband internet has grown from scratch. According to the MIIT, China has built the largest fiber optic and mobile broadband network around the world by the end of 2020, and the penetration rate of internet users exceeded 73% in 2021. These three decades have witnessed colossal success in broadband internet infrastructure construction as well as in internet adoption, which is regarded as a miracle of the development of broadband internet.

On April 20, 1994, the 64K dedicated internet access of the National Computing and Networking Facility of China (NCFC) in Zhongguancun Beijing was connected to the Internet, which marked China's first official access to the global network. Afterward, the Chinese government set forth a battery of policies to support internet development. The "Ninth Five-Year Plan of National Informatization and Visionary Goals for 2010" in 1997 officially recognized the internet as information infrastructure, underscoring its vital role in national economic informatization. In 2001, the Ministry of Industry and Information (MII) unveiled the "Tenth Five-Year Plan of Information Industry", highlighting key achievements up to 2000 and setting ambitious targets for 2000-2005, including expanding domestic fiber optic cable networks, increasing the number of connected computers, and reaching a high internet user penetration rate. The planned investment during this period was 1.7 trillion yuan, with 1.25 trillion yuan allocated to telecommunications. The subsequent "Eleventh Five-Year Plan of Information Industry" in 2007 demonstrated China's substantial progress, including a burgeoning telecommunications network, rapid growth in telephone subscribers, and significant internet user expansion, solidifying China's position as a global player.

The plan set further targets for telephone and internet user growth by 2010. The "Twelfth Five-Year Plan of Internet Industry" in 2012 heralded the tripling of internet users during the "Eleventh Five-Year Plan" period, emphasizing the establishment of super-scale broadband facilities and the proliferation of e-commerce, generating substantial employment opportunities. The "Information and Communication Industry Development Plan (2016-2020)" in 2016 outlined continued growth, with mobile phone penetration, internet user numbers, and broadband accessibility achieving impressive figures. Lastly, the latest "Fourteenth Five-Year Plan of Information and Communication Industry" in December 2021 affirmed China's position as a global leader in internet infrastructure and the successful commercialization of the 5G network, with broadband internet penetration reaching 70.4% in China.

On top of the regular five-year plans, the State Council released the national strategy "China's Broadband Strategic Program and its Implementation Plan" in 2013 to promote the construction of broadband internet nationwide. This program was divided into three phases: speed-up by the end of 2013, popularization in 2014 and 2015, and upgrading from 2016 to 2020. To carry out the "China's Broadband Strategic Program and its Implementation Plan", the Ministry of Industry and Information Technology (MIIT) and the National Development and Reform Commission (NDRC) launched the Broadband China Pilot City Program in January 2014. There were 39 entities designated as "Broadband China Pilot City" each year from 2014 to 2016. The variation in the timing of the designation provides a potential staggered Difference-in-differences (DID) identification design.

2.2 Broadband internet development

Figure 1 depicts the evolution of the spatial distribution of the number of broadband internet subscribers per 100 households and GDP per capita from 2005 to 2019. The pattern of the figures highkights the continual and substaintial growth of both internet subscribers and GDP per capita. The number of cities with broadband internet penetration rates over 70% in 2005 was only 18, and this number increased to 51 after a decade, while in 2019, it surged to 223. During the same sample period, broadband internet penetration, GDP per capita in China also increases rapidly, and presents a similar pattern in terms of both temporal and spatial distribution as broadband internet penetration. Furthermore, Figure 1 reveals the uneven expansion of broadband internet in China. The penetration rate in northeastern China has been left behind the national average throughout the two decades. In contrast the coastal southeastern cities have experienced a fast enhancement in broadband internet penetration starting from 2010 and have been far ahead of the other cities. This paper explores the variation across cities to identify the growth effect of broadband internet penetration.

[Insert Figure 1 here]

3 Growth effect of broadband internet penetration

3.1 Baseline growth model

This paper follows Czernich et al. (2011) that starts from the steady-state equation of a three-input production function proposed by Mankiw et al. (1992):

$$\ln y_{it} = \ln A_{it} + \beta_1 \ln s_{it} + \beta_2 \ln h_{it} + \beta_3 n_{it}, \tag{1}$$

where y_{it} is the output per labor in city i and year t; A_{it} is the level of technology; s_{it} is the share of GDP invested in physical capital; h_{it} is the human capital accumulation; and n_{it} is the growth of labor.

We assume TFP evolves exponentially over the year:

$$A_{it} = A_{i0} \mathrm{e}^{\lambda_{it}}, \tag{2}$$

where A_{i0} is the city-specific initial level of TFP, and $\mathrm{e}^{\lambda_{it}}$ is the growth factor in city i and year t.

Given that broadband internet stimulates innovation and promotes the development of TFP, and this effect needs time to be materialized, we further assume that the growth factor follows:

$$\lambda_{it} = \alpha_0 t + \alpha_1 \ln B_{i,t-1} + \epsilon_{it}, \tag{3}$$

where B_{it-1} is the broadband penetration level in the city i and year $t-1$, that is, the number of broadband subscribers per 100 households.

The intuition behind the Equation (3) is that the city-specific growth of TFP can be divided into three exclusive and exhaustive parts. First, $\alpha_0 t$ is a common growth trend over the whole nation, with an average annual growth rate α_0. Second, $\alpha_1 \ln B_{i,t-1}$ is the contribution of broadband internet penetration in a certain city. Third, ϵ_{it} is an unobserved city- and year-specific term. The term ϵ_{it} captures all factors other than broadband that affect the technology growth, such as the construction of traditional infrastructure like high-speed railways.

The growth of TFP is therefore given by:

$$\Delta \ln A_{it} = \alpha_0 + \alpha_1 \Delta \ln B_{i,t-1} + \Delta \epsilon_{it}, \tag{4}$$

OLS estimates would be consistent if $corr(\Delta \ln B_{i,t-1}, \Delta \epsilon_{it}) = 0$. This assumption is much weaker than $corr(\ln B_{i,t-1}, \epsilon_{it}) = 0$.

Based on the very generalized assumption as Equation (3), Equation (1) becomes:

$$\ln y_{it} = \ln A_{i0} + \alpha_0 t + \alpha_1 \ln B_{it-1} + \beta_1 \ln s_{it} + \beta_2 \ln h_{it} + \beta_3 n_{it} + \epsilon_{it}. \tag{5}$$

By taking the first differences, introducing the output per labor in some initial year (Barro, 1991), and rewriting the first difference of the error term, we propose the economic growth regression model with the impact of broadband internet:

$$\Delta \ln y_{it} = \alpha_0 + \alpha_1 \Delta \ln B_{it-1} + \beta_1 \Delta \ln s_{it} + \beta_2 \Delta \ln h_{it} + \beta_3 \Delta n_{it} + \beta_4 \ln y_{i0} + \varepsilon_{it}. \tag{6}$$

Finally, we get the regression model as Equation (6). The dependent variable $\Delta \ln y_{it}$ is the first difference of the logarithm of GDP per capita of city i in year t, which can be approximately interpreted as the growth rate of GDP per capita of city i in year t. Likewise, the key independent variable $\Delta \ln B_{it-1}$ is the first difference of logarithm or approximately annual growth rate of internet penetration of city i in year $t-1$. Other independent variables include the annual growth rate of saving rate $\Delta \ln s_{it}$, the annual growth rate of human capital intensity $\Delta \ln h_{it}$, the change in population growth rate Δn_{it}, and the logarithm of GDP per capita in some initial year $\ln y_{i0}$. The parameter of our primary interest is α_1, capturing the average effect of broadband internet penetration growth on annual GDP per capita growth, after controlling for other factors. In the set up Equation (6), the first difference eliminates the city fixed effects. We could add a year-fixed effect, and this is only to accommodate α_0 to be year specific. We also test the level model with both year and city fixed-effect as indicated by Equation (5) for robustness check.

3.2 Instrumental variables

The key independent variable in the regression model (6), the broadband internet penetration growth, is endogenous, although the model has taken the first difference. We do not have a prior prediction on the direction of the OLS bias due to reverse causality as it could be two-way. On the one hand, fast-growing cities attract more firms and talent, and they have higher incentives to speed up the construction of broadband internet to provide essential complementarity with larger shares of promising and profitable firms. Those productive firms adopt broadband internet extensively. And the residents have the higher purchasing power of subscribing to broadband internet service. As a result, the broadband penetration in those expansionary cities is expected to grow as well. Hence, a better economic status results in a higher broadband extensive margin, and vice versa. On the other hand, areas with low economic growth rates, especially in rural areas, tend to have poor logistic infrastructure, scattered populations, less productive firms, and limited fiscal budgets. However, China's central government has attached high importance to narrowing the digital divide between urban and rural areas and specifies the requirements for telecommunications universal service in various planning policies including the 13th Fiver-Year Plan for Economic and Social Development of the People's Republic of Chia and the Poverty Alleviation Plan for the 13th Fiver-Year Plan Period. And Regulation of the People's Republic of China on Telecommunications in 2000 stipulates that "telecommunication service operators shall fulfill corresponding telecommunications universal service obligations in accordance with the relevant national provisions."

To address the endogeneity issue, we use the IV estimation to exploit the causal effect of broadband internet penetration on GDP per capita growth. This paper proposes two kinds of IVs that are popular in literature: historical IV and topographical IV. First, the historical IV refers to the variable that contains information from a long time ago. Owning to a longtime interval, the correlation between this historical information and the error term of recent economic status fades away as time goes by. Therefore, historical IV is arguably exogenous. This paper innovatively proposes a historical IV, the number of telephones in 1984. To introduce time variation for panel analysis, it interacts with the lagged first difference of the logarithm of the mean by year (national level) of the endogenous broadband penetration (Nunn and Qian, 2014). The most remote data available at the prefecture city level in the China City Statistical Yearbooks (CCSY) are from 1984. On the one hand, because broadband internet was initially carried by the copper wires of telephones, i.e., copper wires of telephones are the prerequisite of broadband internet service, this predetermined number of telephones is positively related to the broadband internet introduction and popularization later in China. This historical information on the number of telephones in each city, on the other hand, is presumably exogenous to some extent, as China has experienced huge changes after the opening up. Other historical IVs including the number of post offices and telecommunication revenue in 1984 are used as robustness checks. Second, the topographical IV denotes the topographical and geographical characteristics of areas. This kind of variable describes the variations made by nature, as a result, they are usually regarded as exogenous. The novel topographical IV proposed by this paper is the Relief Degree of Land Surface (RDLS) of each city, which is constructed by You et al. (2018). RDLS accounts for both slope and elevation of the terrain: the higher elevation and the higher slope of the terrain, the greater the RDLS. From the engineering perspective, the construction costs of cables are higher for areas with greater RDLS values. Therefore, the relationship between the RDLS and the broadband penetration rate should be negative from the supply side. The RDLS also interacts with the same form of the mean of the endogenous independent variable. Therefore, both the two IVs are valid in terms of exogeneity and relevance.

3.3 Data

We obtain China's prefecture city-level panel data between 2005 and 2019 from CCSY and CEIC databases. In Equation (6), y_{it} is measured by real GDP per capita in the city i and year t, B_{it-1} is the number of broadband internet subscribers per 100 usual households in the city i and year $t-1$, the proxy of k_{it} is the share of fixed asset investment deducted by residential investment in real GDP (all values are deflated), h_{it} is the fraction of enrolled student of higher education institution in a local residence, n_{it} is the growth rate of local residence, and y_{i0} is the real GDP per capita in city i and year 2005.

The key independent variable, the broadband internet penetration B_{it}, is defined as the number of broadband internet subscribers per 100 usual households. Data are collected from the CEIC database and the CCSY database independently, for robustness checks. The explanatory note on the variable broadband internet subscriber does not state explicitly whether it is in terms of household or individual residence. However, generally, there is only one broadband internet subscriber in each household. Therefore, we adopt the number of usual households to normalize the number of broadband internet subscribers. Here, we use usual residence divided by the average household size to infer the number of usual households, where the average household size is calculated as registered population over registered household. The underlying assumption is the average household sizes for registered households and for usual households are the same. In this way, we can obtain the broadband internet penetration rate. According to our sample, the average penetration rates over all cities in 2015 and 2019 are 55.1% and 102.4%, respectively, while the national level penetration rates in 2015 and 2020 released by the Cyberspace Administration of China are 50.3% and 70.4%. This overestimated broadband internet penetration rate is as expected for three reasons. First, the number of broadband internet subscribers collected from the three Telecommunications Service Providers (China Telecom, China Mobile, and China Unicom) includes users from organizations like firms, governments, and universities, which results in double counting for some individuals. Furthermore, this is the reason why the number of broadband internet users is larger than the number of households in cities with a plethora of firms and universities such as Shenzhen, Shanghai, and Wuxi. Second, the average registered household size tends to be larger than the usual household size, since the labor force flows into towns and one registered household breaks out into two usual households in two different cities, for example, reducing the usual household size in each city. Thus, the inferred number of usual households is underestimated, and as a result, the broadband internet penetration rate is overestimated systematically. Lastly, we are short of data for cities with poor economic performance in western China, and they generally have relatively lower internet penetration rates due to either poor economic performance or tough topographic challenges. Consequently, this sample of 241 cities performs better than the nationwide to some extent. In addition, we also use usual residence in each city to normalize the broadband internet users for robustness checks.

[Insert Table 1 here]

The definitions and summary statistics of key variables are reported in Table 1. For those cities with changing boundaries or missing data, we exclude them from our sample (Banerjee et al., 2020). Complete data are available only for 241 cities, and 10 more cities are included if we do not control for investment and education.

4 Results

4.1 Baseline results

According to the structural model Equation (6), we exploit the association between the growth rate of real GDP per capita and the growth rate of broadband internet penetration. The results are reported in Table 2. Column (1) reports the estimates of our baseline model Equation (6). The empirical result indicates that, on average, a 10% increase in the current growth of broadband penetration is associated with a 0.41% increase in real GDP per capita growth in the following year, ceteris paribus. In addition, the signs and magnitudes of coefficients on the other variables are as expected. Column (2) only keeps the key variable of our interest without the other factors of production. Compared with column (1), the coefficient on the lagged growth of broadband penetration in column (2) is less than that in column (1). This is intuitive as the key independent variable is negatively correlated with the control, the first difference of population growth, given that broadband penetration is normalized by population size. Although our structural model Equation (6) is obtained by taking the first difference that eliminates the city fixed effects, we could add a year-fixed effect to show the robustness of our results in column (3). Furthermore, we include both year and city fixed effects and present the results in column (4). The robust and strong evidence suggests that broadband internet penetration growth has a positive association with economic growth.

[Insert Table 2 here]

Broadband internet is a general technology that promotes and compliments the advancement of ICT utilities like personal computers and smartphones. Conversely, it is ICT that exerts the desired effectiveness of broadband internet in production and real life. The commencement of the mobile internet era is the other dramatic driving force of digitalization, during which enormous software and hardware are invented to markedly enhance productivity. Hence, we separate the sample according to the emergence of the third generation of wireless mobile telecommunications technology (3G) and the fourth generation of broadband cellular network technology (4G) in China. Specifically, the year 2010 is regarded as the starting year for 3G because 3G was not commercialized until the 1st October 2009, while the year 2015 for 4G as 4G was commercialized on the 18th March 2014.

[Insert Table 3 here]

Table 3 presents the corresponding OLS regression results. Columns (1)-(3) are the counterparts of Table 2 column (1), closely estimating the structural model (5) with time-separated samples. The results illustrate that before the emergence of 3G, the effect of broadband internet had little association with the GDP per capita growth, i.e., only after the introduction of 3G and/or 4G, the association became significant, and 4G provided a slightly larger effect. This result is pertinent and consistent with our intuition, as ICT utilities are the carriers for broadband internet and the introduction of 3G and 4G enables the public to adopt and utilize broadband internet to come into effect.

4.2 IV results

In this paper, we choose the IV approach to alleviate the endogeneity problem. Table 4 presents the IV regression results. Panel A conducts the second-stage IV regression while panel B reports the first-stage results. Column (1) is the estimation using historical IV, the number of telephones in 1984, column (2) is the RDLS topographical IV, and column (3) includes both IVs to allow for the overidentification test. Panel A of the Table 4 suggests that, in general, a 1% increase in broadband penetration growth promotes the GDP per capita growth by 0.15-0.21%. And interestingly, the growth-enhancing effect of broadband internet is the greatest compared with the physical and human capital investment. The overidentification test of both-IV model guarantees the exogeneity of the IVs. Moreover, the first-stage results in panel B verify the relevance condition of the IV: the historical number of telephones is positively associated with the recent broadband internet penetration, while the tough topographic characteristic is negatively correlated with broadband internet penetration. The reported Kleibergen-Paap rk Wald F statistics for the first-stage regression, with Stock-Yogo critical values 5.53-16.38 for one IV and 7.25-19.93 for two IVs, indicate that there is no concern about the weak IV problem.

[Insert Table 4 here]

The IV coefficients (0.150, 0.207, and 0.162) reported in Table 4 are larger than the OLS coefficient (0.041) as presented in Table 2. The reason is the heterogeneity in the studied group. IV estimator reveals the local average treatment effect (LATE) for compliers (Imbens and Angrist, 1994; Angrist and Pischke, 2009). And in our context, the compliers refer to cities whose broadband internet penetration rates are higher with the greater historical number of telephones and are lower with the tougher topographic characteristics. Hence, the IV coefficients may exceed the OLS counterpart because the compliers enjoy a larger growth effect of broadband internet than the noncompliers. This heterogeneity in the average treatment effect is demonstrated in Table 5 (OLS) and Table 6 (IV). For both tables, since coefficients on internet penetration growth in columns (1), (3), (5) are greater than those in (2), (4), (6) respectively, it is verified that the ATE for compliers is higher than that for non-compliers. Additionally, the estimations in Table 2 and Table 4 are all between the corresponding estimations for compliers and non-compliers.

[Insert Tables 5 and 6 here]

4.3 Robustness checks

We conduct a battery of robustness checks to ensure the robustness of our empirical results. To begin with, we consider the level model with two-way fixed effect as Equation (5). Table A1 presents the OLS and IV results of the level model with two-way fixed effect. Column (1) to (4) are OLS results, while column (5) is the IV result with the historical and topographical IVs. For column (5), the first-stage F statistics is 112.106 with p-value 0.000. The overidentification test p-value is 0.63. Therefore, the effect of broadband internet penetration level on GDP per capita is also highly significant and robust.

[Insert Table A1 here]

Morover, we consider different measures of our independent variable. We collect the number of broadband internet subscribers from CCSY but it does not state explicitly whether the subscriber is in terms of household or individual residence. Here, we change the denominator of broadband internet penetration to the number of usual residents. In addition, we normalize the number of mobile phone users and telecommunication revenue to get the mobile penetration rate and the per capita telecommunication revenue and use them to reveal the growth effects of digital exposure. Tables A2, A3, and A4 mimic Tables 2, 3, and 4, respectively, using the different three measures of the independent variable. The results remain robust.

[Insert Tables A2, A3 and A4 here]

Subsequently, we screen the sample by excluding the cities with strong and endogenous growth effects of broadband internet. Specifically, we exclude Beijing, Shanghai, and Guangzhou as these three cities are the access points to the world's Internet backbone; also, we exclude the eight nodal cities (Beijing, Shanghai, Guangzhou, Shenyang, Nanjing, Wuhan, Chengdu, and Xi'an) of the CHINANET, the largest Internet Backbone Provider (IBP) in China, for the similar reason. The corresponding IV results with four different measures of independent variables are reported in Table A5.

[Insert Table A5 here]

Lastly, since there is a batch of papers that adopts the historical number of post offices in 1984 as an IV for internet penetration, we also use both the post office number and the telecommunication revenue in 1984 as the alternative of our historical IV. The results are still highly robust in these two scenarios (Tables A6 and A7).

[Insert Tables A6 and A7 here]

4.4 A cost-benefit analysis

There is a voluminous literature on the benefits of broadband internet, including encouraging innovation, stimulating productivity, alleviating information asymmetries, improving organizational structure, and promoting management practices. And this considerable evidence serves as underlying channels for the growth effect of broadband internet. However, the overall benefit that aggregates all potential gains needs to be evaluated and compared with the corresponding cost. In the following, we conduct a cost-benefit analysis utilizing our estimation to identify the efficiency of investment in information infrastructure. The conservative OLS baseline result in Table 2 indicates:

$$\Delta \ln y_{it} = 0.041 \Delta \ln B_{it-1} + other factors, \tag{7}$$

which suggests a linear relationship between GDP per capita growth rate and broadband internet penetration growth rate. According to China Statistical Yearbooks, during 2006-2018, the mean of annual growth rate of broadband internet penetration is 19.87%. This translates into an additional increase in annual GDP per capita growth by 0.815% (19.87% times 0.041). We use the sample period mean to calculate the investment efficiency. The average GDP per capita during 2007-2019 is 43,248 yuan, so the increase in GDP per capita due to broadband internet diffusion should be 352.47 yuan (43,248 times 0.815%). If we use the sample period mean of the population, it translates into an increase of approximately 479,835 million in GDP (352.47 × 1361.35 million people). This 479,835 million can be regarded as the benefit of broadband internet diffusion.

According to the MIIT, during 2006-2018, the fixed asset investment in broadband internet infrastructure was 339,342 million, which is the construction cost of broadband internet. Therefore, the rate of return of broadband infrastructure is estimated to be $(479,835 - 339,342)/339,342 \times 100\% = 41.40\%$. This cost-benefit analysis provides important policy implications for China during the digitalization transformation. The investment efficiency of information infrastructure is above the traditional and tangible infrastructure.

5 Mechanisms: Broadband China Pilot City Program

In our structural model, the broadband internet penetration enters the model by affecting productivity, as indicated by Equations (2) and (3). In literature, productivity is one of the most salient channels of economic growth (Gordon, 1999; Kendrick and Sato, 1963). And innovation (Zeira, 1998; Bartel et al., 2007) and entrepreneurship (Leibenstein, 1968; Calvo and Wellisz, 1980; Baumol, 1968) serve as the two potential mechanism. In this section, we provide evidence that the broadband internet promotes both innovation and entrepreneurship, and they are generally regarded as intensive and extensive margins. Leveraging the staggered implementation of the Broadband China Pilot City Program, we examine the intensive margin by evaluating its effect on innovation among incumbent firms and the extensive margin by assessing its impact on entrepreneurial activity. Furthermore, we find that the Broadband China Pilot City Program significantly stimulates the firm-level digital technology adoption.

5.1 Staggered DID identification strategy

The Broadband China Pilot City Program aimed to accelerate the development of broadband infrastructure in China and improve internet access in designated cities. The program was launched in January 2014, with the goal of providing high-speed internet access to all households and promoting the use of broadband technology in various sectors, such as education, healthcare, and e-commerce. All cities at the prefecture level and above, counties under the jurisdiction of municipalities directly under the Central Government, and counties directly under provincial jurisdiction satisfying at least four conditions out of six [1] can apply for the title "Broadband China Pilot City". For the period spanning from 2014 to 2016, a total of 39 cities were designated as "Broadband China Pilot City". During the three-year establishment period, the central government would give priority to these pilot cities in terms of financial support, tax incentives, loan discount financing, broadband universal service compensation, and guidance of local investment. By designating cer-

[1] (i) 20 Mbps and above broadband accessibility rate in an urban area would reach 85%; (ii) 4 Mbps and above broadband accessibility rate in an urban area would reach 90%; (iii) broadband penetration rate would reach 55%; (iv) 3G/LTE mobile phone penetration rate would reach 40%; (v) 4 Mbps and above broadband penetration rate would reach 80%; and (vi) 8 Mbps and above broadband penetration rate would reach 35%.

tain cities as pilot cities, the program aimed to test and demonstrate the feasibility of broadband infrastructure deployment and utilization, with the intention of eventually replicating successful practices across the country. Given the program's multi-period implementation, we adopt a staggered Difference-in-Differences identification strategy to investigate the effect of broadband internet penetration on innovation and entrepreneurship. This approach allows us to estimate the causal impact of the program by comparing the outcomes of treated and control groups before and after the intervention.

In terms of the intensive margin, we employ the growth rate of granted invention patents as the innovation outcome variable. Data on patents are collected by indexing the granted invention patents by city-year from the website of the China National Intellectual Property Administration.[2] Regarding the extensive margin, the internet has a notable positive impact on entrepreneurship, particularly among small and medium-sized firms. To capture the level of entrepreneurship in each city, we utilize the number of newly registered firms with registered capital below 2 million yuan, normalized by the local population. [3] To obtain the data on newly registered firms, we manually collect information on the firms established in each city and year, along with their registered capital, and then aggregate the information at the city-year level. [4]

First, we use the event study approach (ESA) to show the effect of being designated as a "Broadband China Pilot City" on innovation and entrepreneurship. Specifically, we estimate the model:

$$Outcome_{it} = \beta_0 + \sum_{m=2}^{9} \gamma_m T_{i,t-m} + \sum_{n=0}^{5} \gamma_n T_{i,t+n} + \sum_{j} \beta_j X_{jit} + \lambda_i + \mu_t + \varepsilon_{it}. \tag{8}$$

where $Outcome_{it}$ denotes the level of either entrepreneurship or innovation in city i and year t in two separated regressions, and $T_{i,t-m}$ and $T_{i,t+n}$ are year indicators equal to 1 for m (n) year before (after) the city i was designated as "Broadband China Pilot City". Control variables X_{jit} include

[2]The information of granted invention patents was indexed from the website https://pss-system.cponline.cnipa.gov.cn/Disclaimer on the day 20th December 2021).

[3]To test the robustness of our findings, we conduct an additional analysis that considers newly registered firms with registered capital below 0.5 million yuan, and the results demonstrate a consistent pattern.

[4]The information was collected on the platform *Aiqicha* (https://aiqicha.baidu.com/advancesearch) on the day 7th December 2021.

physical capital level, human capital level, and population growth. Our data are between 2007 and 2019, and the first cohort of the "Broadband China Pilot City" was at the year 2014 while the last cohort was in 2016. And we set one year before the designation as the base year. Therefore, m starts from 2 and ends at 9, while n ranges from 0 to 5. The coefficients γ_m and γ_n denote the differences between innovation and entrepreneurship in the never-treated cities and the other cities, respectively, with the absence and presence of being designated as "Broadband China Pilot City".

Second, we estimate a conventional two-way fixed-effects (TWFE) model, which is a widely adopted method in empirical research (Callaway and Sant'Anna, 2021):

$$Outcome_{it} = \alpha_0 + \alpha D_{i,t} + \lambda_i + \mu_t + \varepsilon_{it}. \tag{9}$$

where $D_{i,t}$ is a treatment dummy equal to 1 if city i was ever designated as "Broadband China Pilot City" in year t. And λ_i and μ_t are city and year fixed effects. The parameter of our primary interest is α which captures the average policy effect of the "Broadband China Pilot City" designation on GDP per capita growth.

Third, as there are emerging theoretical research pointing out the drawbacks of TWFE estimation (De Chaisemartin and d'Haultfoeuille, 2020; Callaway and Sant'Anna, 2021; Goodman-Bacon, 2021; Sun and Abraham, 2021), we use the approach proposed by Callaway and Sant'Anna (2021) to estimate the Average Treatment Effect on the Treated (ATT) of being designated as "Broadband China Pilot City" on innovation and entrepreneurship. The key idea of this estimation is to decompose the sample according to the different cohorts of treatment and estimate the Average Treatment Effect (ATE) for each group and time, then aggregate the group-time ATEs into the ATT. This decomposition allows us to observe the changes in the outcome variable over time and how they relate to the timing of treatment, providing a more nuanced understanding of the treatment effect.

Specifically, we estimate the group-time average treatment effects $ATT(g,t)$ for all $t \geq g$:

$$ATT(g,t) = E\left[Outcome_t - Outcome_{g-1} \mid G = g\right] - E\left[Outcome_t - Outcome_{g-1} \mid C = 1\right] \tag{10}$$

where G is defined as the year when a city was designated as a "Broadband China Pilot City", which denotes the cohort of the "Broadband China Pilot Cities", and $G \in 2014, 2015, 2016$ in our setup. For cities that were never designated, we set $G = 0$. G_{ig} is the dummy variable equal to one if a city i is designated in period g, i.e., $G_{ig} = \mathbf{1}\{G_i = g\}$. C_i is an indicator equal to one if city i has never been selected as the "Broadband China Pilot City", i.e., $C_i = \mathbf{1}\{G_i = 0\}$, serving as the control group in this setting. We further allow for anticipation in our setting, and the anticipation horizon is denoted as δ.

Subsequently, we aggregate the ATE separately for each group:

$$\theta(g) = \frac{1}{\mathcal{T} - g + 1} \sum_{t=2}^{\mathcal{T}} \mathbf{1}\{g \leq t\} ATT(g, t) \tag{11}$$

where $\mathcal{T}$ is the total time periods.

Finally, we compute the overall effect across all groups:

$$\theta^O := \sum_{g=2}^{\mathcal{T}} \theta_S(g) P(G = g) \tag{12}$$

We also aggregate for each year exploiting different versions of aggregation provided by Callaway and Sant'Anna (2021). The overall treatment effect θ^O reflects the effect of the Broadband China Pilot City Program across all groups that have ever been designated as "Broadband China Pilot City".

5.2 Empirical results for mechanism

We report the empirical results of the staggered DID design to explore the causal effect of broadband internet on innovation and entrepreneurship, the two potential channels of economic growth.

For the event study modeled by Equation (8), Figures 2 and 3 for innovation and entrepreneurship respectively illustrate that all the coefficients γ_ms are not significantly different from zero. Furthermore, at the year of designation and at least the following construction period for three years, the coefficients are significantly positive, which is consistent with our preliminary expectation. The parallel trend assumption is met, conditional on the set of controls.

[Insert Figures 2 and 3 here]

The staggered DID results of innovation and entrepreneurship are addressed in Tables 7 and 8, respectively.

Regarding the extensive margin, Panel A of Tables 7 and 8 report the innovation and entrepreneurship results respectively under the unconditional parallel trend assumption. It requires no significant difference in entrepreneurship growth trends between Broadband China Pilot Cities and the others in the absence of the program. The p-value for this pre-trend test is 0.001, which indicates that the cities perform quite differently in terms of entrepreneurship. Hence, we report the estimations in panel B under the parallel trend assumption conditional on the pre-treatment level of physical capital, human capital, and population growth. The p-value for conditional parallel trend assumption is 0.128, which provides a more confident causal inference.

The rows "TWFE" in both panels of Tables 7 and 8 present treatment effects estimated by the two-way fixed-effects regression model, as described in Equation (9). The conventional TWFE estimations suggest a statistically significant positive effect of being designated as a "Broadband China Pilot City" on innovation and entrepreneurship, reflected as the intensive margin and extensive margin. Following Callaway and Sant'Anna (2021), we also report the aggregated group-time average treatment effects in Tables 7 and 8. For the intensive margin, the simple average aggregation in Table 8 suggests that the Broadband China Pilot City Program makes the innovation level of the pilot cities 7.4%-13.9% higher than the others. As for the extensive margin, the simple average of the treatment effect in Table 7 is 0.312-0.548, indicating that the entrepreneurial activity in cities that have been designated as a "Broadband China Pilot City" is significantly enhanced, and, on average, is 31.2%-54.8% higher than those who have not.

Additionally, we illustrate the heterogeneous policy effects by calculating the partially aggregated estimates. In general, the three methods of aggregation, namely by cohort, calendar year, and length of exposure, consistently suggest the same positive patterns as the TWFE and simple average estimations. In particular, the rows "Cohort-Specific Effects" report ATEs for the three cohorts (2014, 2015, and 2016) of Broadband China Pilot Cities. The rows "Calendar Year Effects" report ATEs by calendar year, while the rows "Event Study" address ATEs by the length of exposure to the Broadband China Pilot City Program. An interesting and intuitive story behind the difference between Tables 7 and 8 is that broadband internet benefits entrepreneurship immediately, while the benefits of innovation take a longer time to materialize. Broadband internet enables a variety of access to sales channels, convenient online payment platforms, and efficient electronic information systems. Entrepreneurs are quick to capitalize on these opportunities brought by broadband internet. As a result, we observe an instantaneous increase in the number of newly-registered small-and-medium-sized firms, which is a key measure of entrepreneurship in our analysis. In contrast to entrepreneurship, innovation is a more complex and time-consuming process that cannot be achieved through simple capital investments. The effects of broadband internet on innovation take time to be fully revealed. In our analysis, we use the number of filed invention patents as a proxy for innovation. Among the three categories of patents, namely invention patents, design patents, and utility models, invention patents embody the most intense innovations, but they also take longer to be discovered. It typically takes at least 20 months for a filed invention patent to be granted by China National Intellectual Property Administration as reported.[5] Thus, in Table 8, we only observe significant effects of broadband internet on innovation starting from the third year of exposure to the Broadband China Pilot City Program.

[Insert Tables 7 and 8 here]

A weakness of DID approach is the biased standard errors due to autocorrelation, which results in over-rejection of no treatment effect (Bertrand et al., 2004). In this paper, we follow Chetty et al. (2009); Cantoni et al. (2017); Li et al. (2016) and perform a nonparametric placebo test by imitating the procedure of the Broadband China Pilot City Program but randomly assigning the "Broadband China Pilot City" titles to cities. Specifically, we randomly designate 39 cities to be Broadband China Pilot Cities each of the three years without replacement, and once a city is selected it is dropped from the set for the next cohort's designation. Therefore, in this generated dataset, there are 39 cities in each year selected as "Broadband China Pilot Cities", serving as a placebo treatment group. The estimated pseudo-treatment effect is expected to be insignificant

[5]Source: https://www.tradecommissioner.gc.ca/china-chine/118690.aspx?lang=eng

with a magnitude of zero. This exercise is repeated 1,000 times to obtain 1,000 placebo estimates. We separately conduct this placebo test for innovation and entrepreneurship. Figures 4 and 5 show the empirical cumulative distribution functions (cdf) and probability density functions (pdf) of these placebo effects on innovation and entrepreneurship respectively, juxtaposed with the vertical solid lines denoting the benchmark two-way fixed-effects estimates, from Panel B of Tables 7 and 8 respectively.

[Insert Figures 4 and 5 here]

The distribution of the placebo effects from random designation are centered around zero, and each of the benchmark estimates is reported in Tables 7 and 8 lies outside the entire distribution estimated by our placebo procedure. Hence, these results increase our confidence that the significantly positive intensive and extensive margins are not spuriously driven by biased standard errors.

5.3 Cross-validation test of main results

In this section, we establish a connection between the evidence that the Broadband China Pilot City Program stimulates firm innovation and entrepreneurship and our main finding that broadband internet has a significant growth effect. To do this, we conduct a cross-validation test to assess whether the program enhances broadband penetration growth and GDP per capita growth using the staggered DID framework, utilizing the staggered rollout of the Broadband China Pilot City Program.

Specifically, we adopt the same methodology as described in Equations (10), (11), and (12), with the outcome variables being the dependent variables and the key independent variables aligning with those in our main regression model Equation (6), i.e., the annual growth of GDP per capita and broadband internet penetration. The results are presented in Table 9.

[Insert Table 9 here]

Panel A presents the effect on broadband penetration growth, while Panel B focuses on GDP per capita growth. The table format mirrors that of Tables 7 and 8. Regardless of whether we consider the conventional TWFE or the modified DID method for multi-period implementation, our findings indicate that the Broadband China Pilot City Program indeed leads to an increase in broadband penetration growth in the pilot cities following its implementation, which aligns with the basic policy expectations and targets. Moreover, this program also generates an increase in GDP per capita growth. Our analysis throughout this paper elucidates the underlying mechanisms behind the growth effect.

5.4 Digital adoption of firms

In this section, we investigate the effect of the Broadband China Pilot City Program on digital adoption among firms. This represents a logical extension following our discovery that this program stimulates innovation and entrepreneurship. We aim to examine the fundamental mechanisms through which the program encourages and facilitates firms to integrate digital technologies into their business operations.

To carry out this analysis, we collect datasets that encompass firms engaged in various digital activities before 1st January 2020. These activities include the operation of WeChat applets, commonly known as WeChat Mini Programs, which are applications seamlessly integrated into WeChat without requiring separate downloads or installations. Additionally, we consider firms that develop and use standalone applications, possess Internet Content Provider (ICP) licenses from MIIT, and hold computer software copyrights, operate Sina Weibo Accounts and WeChat Official Accounts. Sina Weibo is a prominent microblogging social media platform in China and WeChat Official Account is official profile based on the WeChat platform. Both platforms enable businesses, organizations, and individuals to establish and manage accounts for the purpose of information dissemination, engagement with followers, and conducting marketing and communication. Whether firms embrace these digital technologies at the enterprise level serve as indicators of their levels of digitization. We aggregated the number of firms participating in these six categories of digital technologies and social media channels at the city level. These counts are then normalized by the total number of firms operating within each respective city. The datasets of firms lists are aquired from *Qi Cha Cha* website [6] by the built-in function of advanced search. It is an official enterprise credit information query system in China, registered with the government as an enterprise credit reporting agency.

Our empirical analysis employs a long-difference regression model from 2006 to 2019:

$$\ln Adoption_{i,k} = \pi_{0jk} + \rho_{j,k} BC_{i,j} + \pi_{1jk}\Delta \ln Y_i + \pi_{2jk}\Delta \ln L_i + \pi_{3jk}\Delta h_i + \upsilon_{ijk}, k = 1, \dots, 6; j = 1, 2 \tag{13}$$

where $Adoption_{i,k}$ is the share of firms with applets ($k = 1$), applications ($k = 2$), ICP licenses ($k = 3$), software copyrights ($k = 4$), Weibo Accounts ($k = 5$) and WeChat Official Accounts ($k = 6$) in city i at the end of year 2019. We assume that in the year 2006, these six categories of digital technology was rarely available and therefore the level of digital adoption is arguably assumed to be zero in the initial year 2006. Thus, $Adoption_{i,k}$ can be regarded as the long-difference of the firms' digital adoption behavior over the sample period 2006-2019. $\Delta \ln Y_i$ is the change in the natural logarithm of GDP in 2019 relative to 2006 in city i; $\Delta L_i$is the change in population size, that is, the natural logarithm of usual residence in 2019 relative to 2006 in city i; and $\Delta h_i$is the change in human capital, which is measured by the share of students enrolled in higher education institutions in usual residence in 2019 relative to 2006 in city i. The key dependent variables $BC_{i,j}, j = 1, 2$ are defined as follows:

$$BC_{i,1} = \begin{cases} 1, & \text{city } i \text{ was designated as a "Broadband China Pilot City"} \\ 0, & \text{otherwise} \end{cases}$$

$$BC_{i,2} = \begin{cases} 3, & \text{city } i \text{ was in the 2014 cohort} \\ 2, & \text{city } i \text{ was in the 2015 cohort} \\ 1, & \text{city } i \text{ was in the 2016 cohort} \\ 0, & \text{otherwise} \end{cases}$$

The Equation (13) is a reduced-form long-difference regression model. In this context, concerns related to reverse causality are minimal, as it is highly improbable that the firms' adoption of the abovementioned six categories of digital technologies and social media platforms would exert an

[6] See https://www.qcc.com

substantial influence on the city-level participation in the Broadband China Pilot City Program. After controlling for fundamental city-level characteristics, our primary focus of the key parameters are denoted as $\rho_j, j = 1, 2$. The coefficients elucidate the impact of the Broadband China Pilot City Program on the adoption of digital technologies and social media platforms by firms.

[Insert Table 10 here]

The findings are displayed in Table 10. In Panel A, we present the results of the long-difference regression, with particular emphasis on the key independent variable, denoted as BC_1 or BC dummy, i.e., a binary indicator discerning whether a city participated in the Broadband China Pilot City Program. In Panel B, our focus shifts to the key independent variable BC_2 which we refer to as BC order in the table, which is an ordered categorical variable with values of 0, 1, 2, and 3, corresponding to distinct program participation timing: cities that never participated in the program, those that joined in the last batch (in the year 2016), the second batch (in the year 2015), and the first batch (in the year 2014), respectively. Columns (1) through (6) in the table correspond to different values of k ranging from 1 to 6. In each case, the dependent variable represents the proportion of firms engaged in various activities, including applets, applications, ICP licenses, software copyrights, Weibo Accounts, and WeChat Official Accounts. To ensure comparability across columns, we employ the natural logarithm of the dependent variable. This transformation enables us to interpret the coefficients as semi-elasticities, facilitating meaningful comparisons across different categories. After controlling the other factors, our results in Table 10 suggests the positive and strong effect of the Broadband China Pilot City Program on firm's digital adoption, regardless of the category of digital technologies. Table 10 sugegsts that firms located in Broadband China Pilot Cities exhibit significantly elevated digital adoption levels, ranging from 37.4% to 79.0%, ceteris paribus. Furthermore, businesses operating in cities that participated in the program at an earlier stage experience even higher levels of digital adoption.

6 Conclusion

In the digital age, the importance of broadband internet infrastructure is widely recognized. This paper is driven by the question of whether investing in broadband internet infrastructure yields substantial rewards in China. We develop a structural model and estimate the relationship between broadband internet penetration growth and economic growth, shedding light on the power of digital infrastructure. To adress the endogeneity issue, we adopt two valid instrumental variables and find robust results. In such a framework, we estimate that a 10% increase in broadband internet penetration growth is associated with a 0.41% increase in annual GDP per capita growth. A cost-benefit analysis translates this estimate into an average rate of return of approximately 40% for investments in broadband internet infrastructure in China, emphasizing both the potential and rewarding nature of such investments in fueling China's economic development.

Furthermore, our exploration of the temporal and spatial variations provided by the Broadband China Pilot City Program has revealed the underlying mechanisms driving this growth effect. It becomes evident that broadband internet not only accelerates firms' digital adoption, but also plays a pivotal role in fostering both innovation and entrepreneurship.

This paper contributes to the expanding literature on the relationship between digital infrastructure and economic growth and addresses the challenge of reverse causality using two robust instrumental variables. Additionally, it assesses the efficiency of investments in digital infrastructure from the perspective of public infrastructure, offering valuable insights for policymakers.

As we navigate the dynamic landscape of technological advancements and their profound implications for economic growth, the findings presented here underscore the vital importance of continued investments in digital infrastructure. They highlight the transformative potential of broadband internet and emphasize the need for strategic policies that facilitate its widespread deployment. In an era where digitalization is reshaping industries and societies, our research adds to the ongoing discourse regarding the role of technology in driving sustainable economic development.

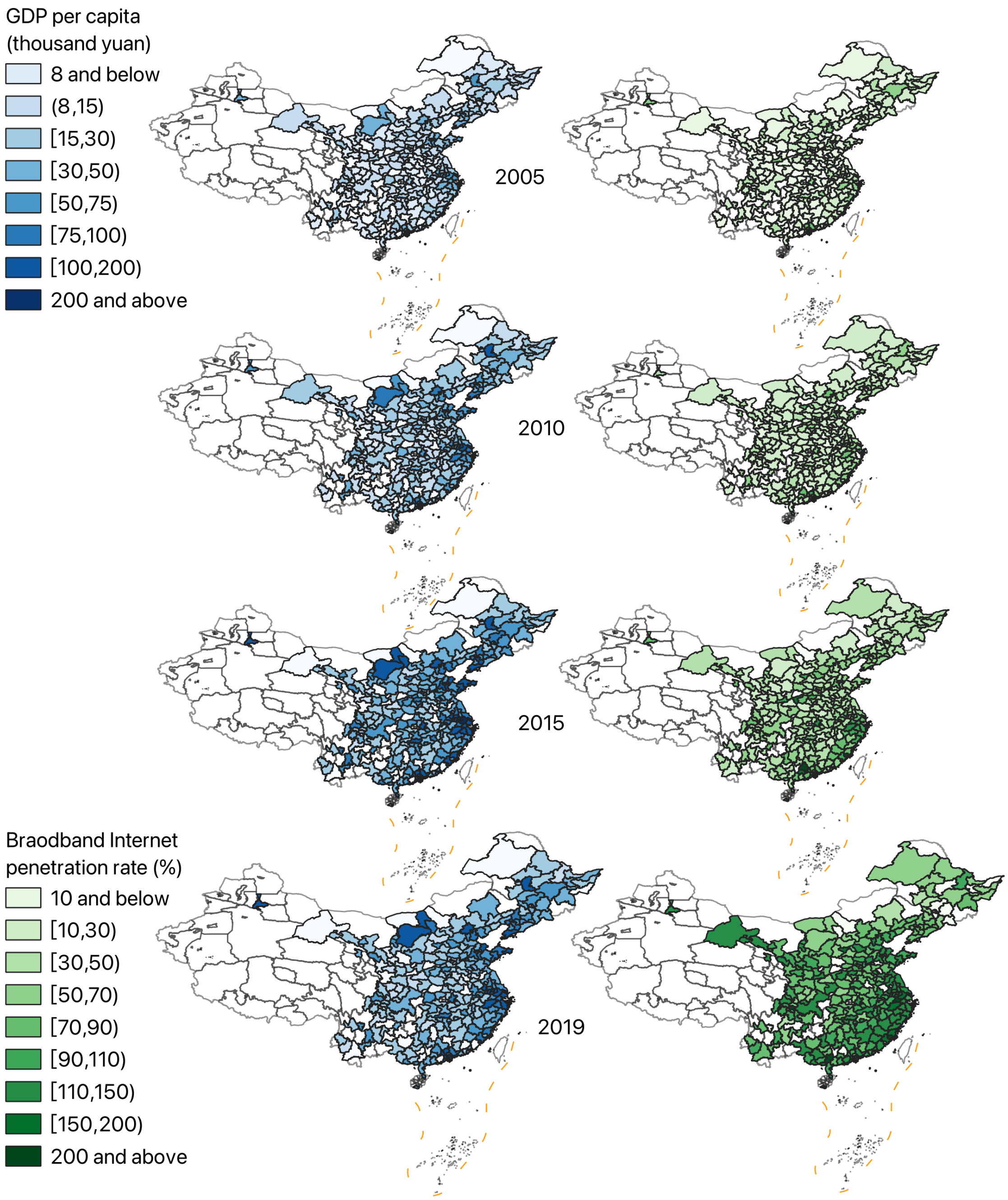

Figure 1: The spatial distribution of broadband penetration (left panel) and GDP per capita (right panel)

Notes: 1. The left panel reflects broadband penetration, which is defined as the number of broadband internet subscribers per 100 households. The right panel is GDP per capita, and the unit is thousand yuan. 2. The areas with data unavailable are colored in white. 3. Regions with darker color have greater values of broadband penetration or GDP per capita. *Source:* Calculated by authors according to the China City Statistical Yearbooks and the CEIC database.

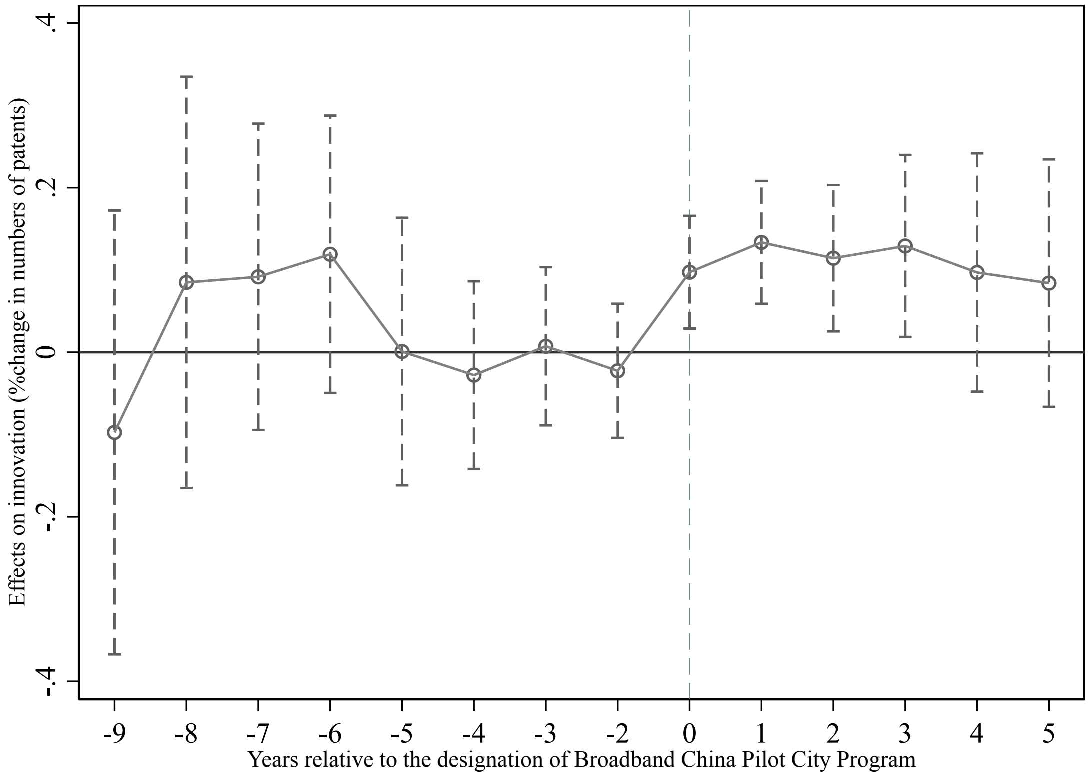

Figure 2: Pretrend of the Broadband China Pilot City Program on entrepreneurship

Note: The 90% confidence intervals are represented by dashed lines.

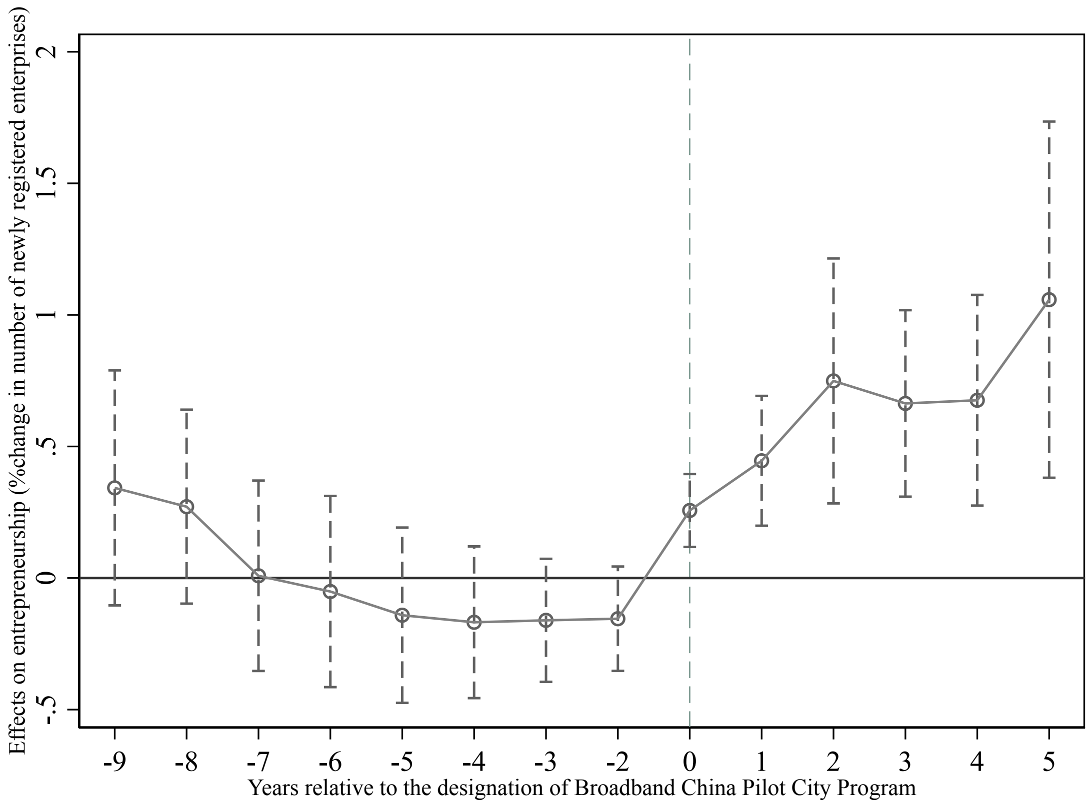

Figure 3: Pretrend of the Broadband China Pilot City Program on innovation

Note: The 90% confidence intervals are represented by dashed lines.

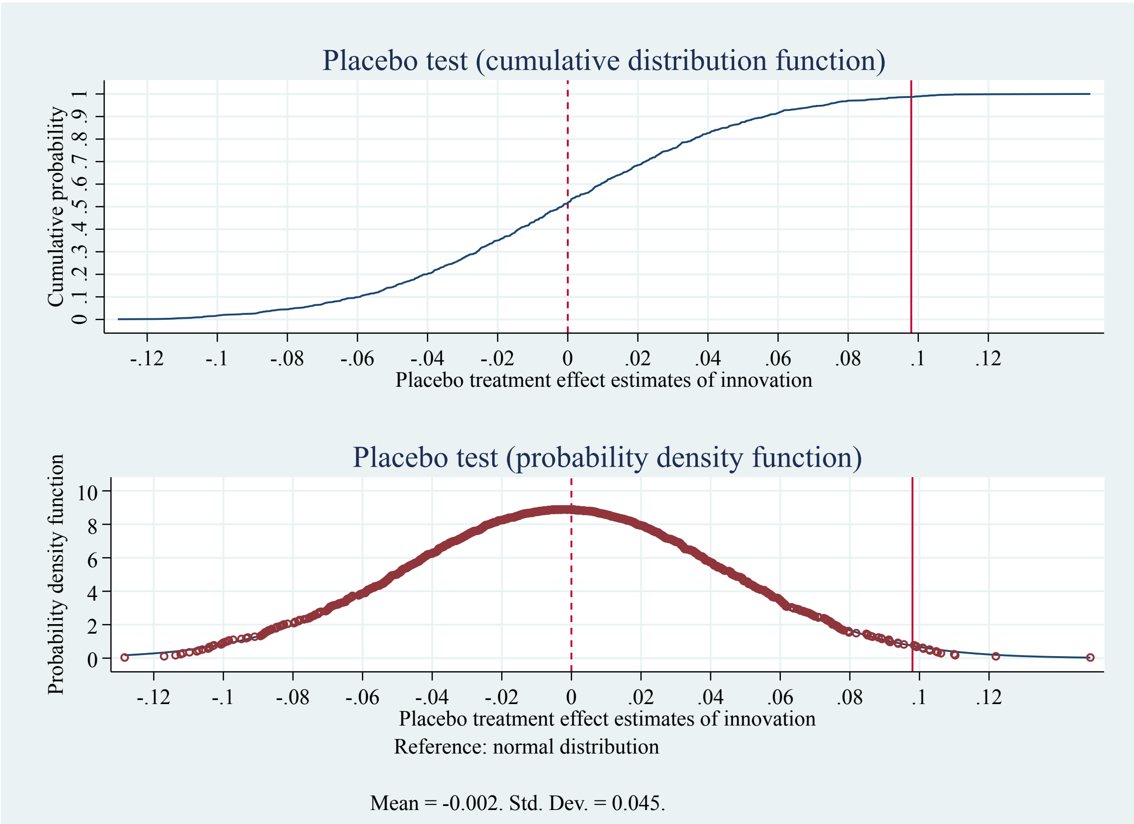

Figure 4: Placebo Broadband China Pilot City: Distribution of Estimated Coefficients regarding entrepreneurship

Note: This figure plots the cdf (top panel) and the pdf (bottom panel) of the placebo effects of 1000 times random Broadband China Pilot City designation on the city-level entrepreneurship.

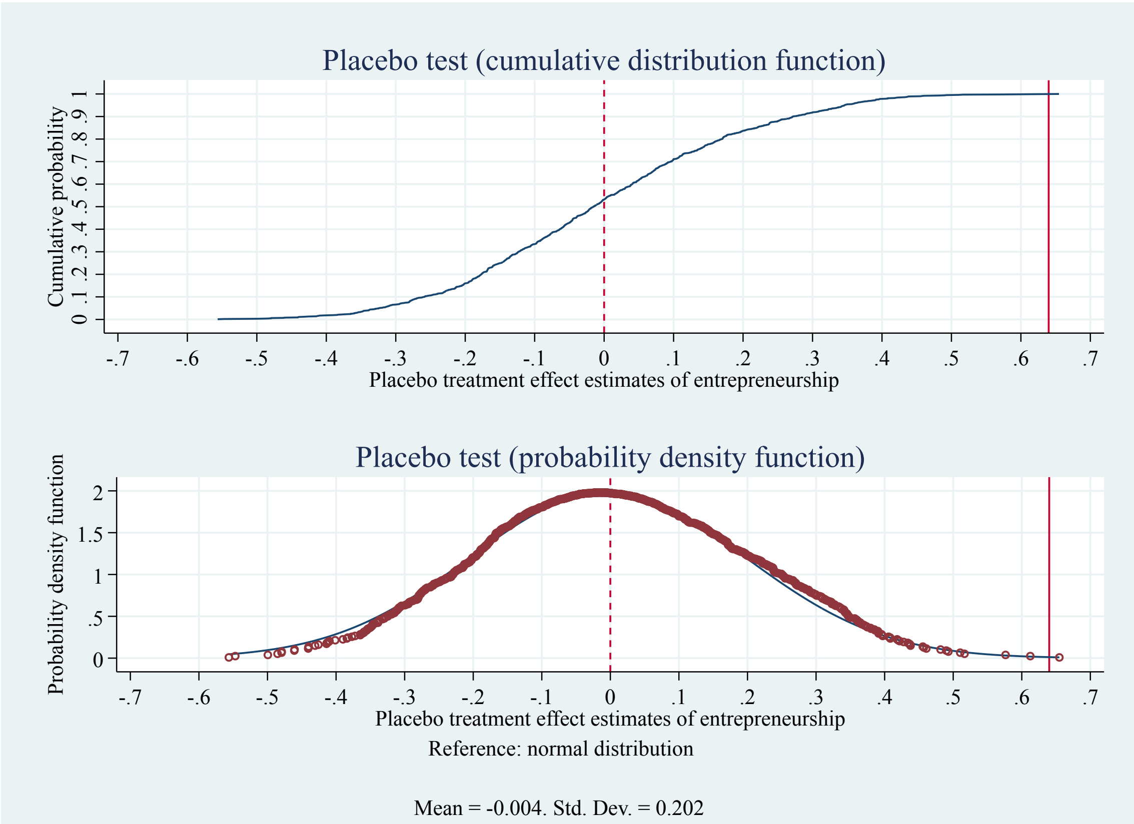

Figure 5: Placebo Broadband China Pilot City: Distribution of Estimated Coefficients regarding innovation

Note: This figure plots the cdf (top panel) and the pdf (bottom panel) of the placebo effects of 1000 times random Broadband China Pilot City designation on the city-level innovation.

Table 1: Summary statistics

Variables	Definition	N	P25	Mean	Median	P75	Std. Dev.
$\Delta \ln y$	Growth rate of deflated GDP per capita	2862	5.794	8.602	8.702	11.981	6.402
$\Delta \ln B$	Growth of broadband penetration (denominator is usual household)	2862	5.208	15.227	14.107	23.921	17.722
$\Delta \ln b$	Growth of broadband penetration another measure (denominator is usual residence)	2862	5.956	15.847	14.761	24.879	17.624
$\Delta \ln M$	Growth of mobile phone penetration	2862	1.592	10.446	8.696	17.258	15.967
$\Delta \ln R$	Growth of per capita telecommunication revenue	2792	-0.534	6.259	5.854	12.270	19.392
$\Delta \ln k$	Growth of the share of deflated fixed asset minus residential investment in deflated GDP	2862	-3.521	2.869	5.122	11.436	17.87
$\Delta \ln h$	Growth of the share of students enrolled in higher education institutions in usual residence	2862	-0.321	5.543	3.656	9.65	14.759
Δn	First difference of usual residence growth	2862	-0.635	-0.064	0.001	0.586	4.455
$\ln y_0$	Logarithm of GDP per capita in 2005	2862	8.901	9.361	9.311	9.726	0.629

Notes: 1. All the growth rates are obtained by the differences between the logarithm of the current-year value and the previous-year value, and in terms of percentage %.
2. Data source: CEIC database.

Table 2: Broadband penetration growth and GDP per capita growth (OLS): baseline

Dep: GDP per capita growth	(1) Baseline	(2) No control	(3) Baseline with year FE	(4) Baseline with TWFE
Lag of broadband penetration growth	0.041***	0.027***	0.041***	0.018***
	(0.007)	(0.007)	(0.008)	(0.007)
Saving rate growth	0.131***		0.127***	0.102***
	(0.014)		(0.016)	(0.018)
Human capital growth	0.033***		0.035***	0.022**
	(0.009)		(0.010)	(0.010)
First-difference of population growth	-0.307***		-0.310***	-0.304***
	(0.030)		(0.031)	(0.030)
Logarithm of GDP per capita in 2005	-1.324***	-1.915***		
	(0.174)	(0.174)		
Constant	19.549***	25.841***	7.166***	9.010***
	(1.689)	(1.644)	(0.149)	(0.349)
City FE	NO	NO	NO	YES
Year FE	NO	NO	YES	YES
Observations	2,608	2,608	2,608	2,608
R-squared	0.221	0.046	0.182	0.347

Notes: 1. Clustered (at city level) robust standard errors are reported in parentheses.
2. $***$ indicates $p < 0.01$; $**$ indicates $p < 0.05$; $*$ indicates $p < 0.1$.
3. Column (1) is the baseline results, which includes all variables in the structural model. Column (2) only include the key independent variable and the GDP per capita in the initial year 2005. Column (3) controls for year fixed effect. And column (4) includes both year and city fixed effect.

Table 3: Growth effect of broadband internet: considering 3G and 4G introduction

	(1)	(2)	(3)	(4)	(5)	(6)
Dep: GDP per capita growth	Before 3G: 2006-2009	3G-4G: 2010-2014	After 4G: 2015-2019	Before 3G: 2006-2009	3G-4G: 2010-2014	After 4G: 2015-2019
Lag of broadband penetration growth	0.002	0.046***	0.047***	0.007	0.041***	0.062***
	(0.012)	(0.009)	(0.018)	(0.012)	(0.008)	(0.020)
Saving rate growth	0.066***	0.021	0.122***	0.086***	0.068***	0.134***
	(0.020)	(0.016)	(0.020)	(0.023)	(0.016)	(0.023)
Human capital growth	0.036**	0.004	0.029	0.045***	0.013	0.037
	(0.018)	(0.012)	(0.024)	(0.016)	(0.014)	(0.027)
First-difference of population growth	-0.279***	-0.339***	-0.288***	-0.284***	-0.310***	-0.297***
	(0.046)	(0.036)	(0.080)	(0.049)	(0.035)	(0.080)
Logarithm of GDP per capita in 2005	-1.341***	-1.878***	-1.430***			
	(0.478)	(0.235)	(0.429)			
Constant	22.443***	26.270***	17.610***	9.054***	10.545***	4.009***
	(4.634)	(2.257)	(4.005)	(0.412)	(0.416)	(0.464)
Year FE	NO	NO	NO	YES	YES	YES
R-squared	0.127	0.165	0.229	0.113	0.270	0.230
Observations	680	1,132	796	680	1,132	796

Notes: 1. Clustered (at city level) robust standard errors are reported in parentheses.
2. $***$ indicates $p < 0.01$; $**$ indicates $p < 0.05$; $*$ indicates $p < 0.1$.
3. Column (1) reports the estimation of time period 2006-2009 (inclusive). Column (2) is for 2010-2014 (inclusive). And column (3) is for 2015-2019 (inclusive).

Table 4: The effect of broadband penetration growth on GDP per capita growth (2SLS)

	(1) Historical IV	(2) Topographical IV	(3) Both IVs
Panel A			
Lag of broadband penetration growth	0.150***	0.207***	0.162***
	(0.043)	(0.053)	(0.038)
Saving rate growth	0.145***	0.147***	0.145***
	(0.017)	(0.017)	(0.015)
Human capital growth	0.037***	0.035***	0.037***
	(0.012)	(0.013)	(0.013)
First-difference of population growth	-0.382***	-0.414***	-0.389***
	(0.048)	(0.050)	(0.056)
Logarithm of GDP per capita in 2005	-0.782**	-0.472	-0.719**
	(0.324)	(0.365)	(0.281)
Constant	12.808***	9.064**	12.050***
	(3.621)	(4.121)	(3.075)
Overidentification p-value			0.308
Observations	2,090	2,090	2,090
R-squared	0.147	0.031	0.127
Panel B			
Historical IV	8.047***		7.070***
	(0.881)		(0.882)
Topographical IV		-11.524***	-6.016***
		(1.544)	(1.584)
Controls	YES	YES	YES
Kleibergen-Paap rk Wald F statistics	83.529	55.714	45.999
Observations	2,090	2,090	2,090
R-squared	0.095	0.069	0.099

Notes: 1. Clustered (at city level) robust standard errors are reported in parentheses.
2. $***$ indicates $p < 0.01$; $**$ indicates $p < 0.05$; $*$ indicates $p < 0.1$.
3. Panel A performs the second-stage IV regression while panel B presents the first-stage results. Column (1) is the estimation using historical IV, the number of telephone users in 1984, column (2) is the topographical RDLS IV, and column (3) includes both historical and topographical IVs to allow for the overidentification test.

Table 5: The average treatment effect for compliers versus non-compliers (OLS)

	(1) IV1 complier	(2) IV1 non-complier	(3) IV2 complier	(4) IV2 non-complier	(5) IVs complier	(6) IVs non-complier
Lag of broadband penetration growth	0.061***	0.032***	0.040***	0.035***	0.054***	0.036***
	(0.020)	(0.008)	(0.010)	(0.013)	(0.020)	(0.009)
Saving rate growth	0.146***	0.137***	0.122***	0.160***	0.153***	0.136***
	(0.026)	(0.022)	(0.023)	(0.025)	(0.034)	(0.019)
Human capital growth	0.046**	0.040***	0.029*	0.053***	0.031	0.042***
	(0.018)	(0.014)	(0.016)	(0.015)	(0.026)	(0.012)
First-difference of population growth	-0.465***	-0.243***	-0.288***	-0.351***	-0.410***	-0.303***
	(0.061)	(0.036)	(0.046)	(0.052)	(0.056)	(0.043)
Logarithm of GDP per capita in 2005	-1.990***	-1.263***	-1.464***	-1.143***	-1.699***	-1.410***
	(0.315)	(0.266)	(0.352)	(0.291)	(0.539)	(0.231)
Constant	25.720***	18.979***	21.114***	17.585***	23.071***	20.359***
	(3.125)	(2.587)	(3.287)	(2.923)	(5.054)	(2.270)
Observations	696	1,407	1,032	1,071	420	1,683
R-squared	0.268	0.229	0.191	0.270	0.259	0.233

Notes: 1. Clustered (at city level) robust standard errors are reported in parentheses.
2. $***$ indicates $p < 0.01$; $**$ indicates $p < 0.05$; $*$ indicates $p < 0.1$.
3. IV1 is the historical number of telephones, and IV2 is the RDLS. We first binarize the two IVs and the endogenous independent variable. Specifically, For IV1, we separate the cities according to the median of the historical number of telephones. IV2 is compared with one, considering the geographic meaning of the RDLS. RDLS equals one for the benchmark mountain that is the dividing elevation between mountain and hill in Landform Classification System of China. RDLS greater (less) than one means that the relief degree is higher (lower) than the height of a benchmark mountain. As for the endogenous variable, we divide the cities based on the median of the sample period average of internet penetration growth. Then, we define the compliers as those cities fall into the same upper or lower percentile of IV1 and internet penetration growth (IV1 complier), and different upper or lower percentiles of IV2 and internet penetration growth (IV2 complier), and both compliers for IV1 and IV2 are regarded as the IVs compliers. For IV1, there are 65 compliers out of 197 cities. For IV2, there are 96 compliers verses 101 non-compliers. And 38 cities are compliers when considering both IVs. Coefficients on internet penetration growth in columns (1) (3) (5) are greater than those in (2) (4) (6) respectively, and the baseline OLS estimation is 0.041 in column (1) of Table 2. Therefore, ATE for compliers appears to be systematically higher than that for non-compliers, and IV results are greater than OLS results.

Table 6: The average treatment effect for compliers versus non-compliers (IV)

	(1) IV1 complier	(2) IV1 non-complier	(3) IV2 complier	(4) IV2 non-complier	(5) IVs complier	(6) IVs non-complier
Lag of broadband penetration growth	0.198***	0.133***	0.169***	0.127***	0.245***	0.139***
	(0.064)	(0.048)	(0.053)	(0.048)	(0.080)	(0.043)
Saving rate growth	0.147***	0.143***	0.166***	0.125***	0.150***	0.141***
	(0.025)	(0.023)	(0.025)	(0.023)	(0.030)	(0.020)
Human capital growth	0.054***	0.034**	0.050***	0.028	0.045	0.038***
	(0.020)	(0.016)	(0.016)	(0.018)	(0.032)	(0.014)
First-difference of population growth	-0.555***	-0.296***	-0.411***	-0.348***	-0.537***	-0.359***
	(0.081)	(0.047)	(0.062)	(0.061)	(0.107)	(0.052)
Logarithm of GDP per capita in 2005	-1.650***	-0.594	-0.603	-1.092***	-1.618**	-0.776**
	(0.444)	(0.404)	(0.372)	(0.419)	(0.702)	(0.353)
Constant	20.483***	11.200**	10.889***	16.087***	19.063***	12.910***
	(4.899)	(4.421)	(4.058)	(4.403)	(6.951)	(3.876)
Observations	696	1,407	1,032	1,071	420	1,683
R-squared	0.167	0.139	0.125	0.159	0.071	0.145

Notes: 1. Clustered (at city level) robust standard errors are reported in parentheses.
2. $***$ indicates $p < 0.01$; $**$ indicates $p < 0.05$; $*$ indicates $p < 0.1$.
3. The definitions of compliers and noncompliers are the same as Table 5.

Table 7: Mechanism: Broadband China ATE on entrepreneurship

Panel A: under the unconditional parallel trend assumption							
	Aggregated Effect	Partially Aggregated Parameter					
TWFE	0.660***						
	(0.118)						
Simple Average	0.548***						
	(0.143)						
Cohort-Specific Effect		g=2014	g=2015	g=2016			
	0.486***	1.110***	0.180	0.165			
	(0.122)	(0.291)	(0.132)	(0.153)			
Calendar Year Effect		t=2014	t=2015	t=2016	t=2017	t=2018	t=2019
	0.558***	0.646***	0.522***	0.666***	0.505***	0.443***	0.564***
	(0.141)	(0.188)	(0.175)	(0.221)	(0.141)	(0.152)	(0.180)
Event Study		e=0	e=1	e=2	e=3	e=4	e=5
	0.625***	0.279***	0.438***	0.682***	0.546***	0.606***	1.197***
	(0.156)	(0.078)	(0.130)	(0.232)	(0.164)	(0.200)	(0.364)
Panel B: under the conditional parallel trend assumption							
	Aggregated Effect	Partially Aggregated Parameter					
TWFE	0.640***						
	(0.118)						
Simple Average	0.312*						
	(0.184)						
Cohort-Specific Effect		g=2014	g=2015	g=2016			
	0.277*	0.590	0.149	0.069			
	(0.164)	(0.381)	(0.143)	(0.169)			
Calendar Year Effect		t=2014	t=2015	t=2016	t=2017	t=2018	t=2019
	0.335*	0.502**	0.372*	0.536**	0.292	-0.002	0.310
	(0.176)	(0.206)	(0.209)	(0.254)	(0.197)	(0.323)	(0.204)
Event Study		e=0	e=1	e=2	e=3	e=4	e=5
	0.329*	0.229***	0.311**	0.497*	0.303	0.034	0.598
	(0.198)	(0.086)	(0.151)	(0.276)	(0.212)	(0.399)	(0.402)

Notes: 1. Bootstrapped standard errors clustered at the city level are reported in parentheses.
2. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.
3. This table reports the effects of the Broadband China Pilot City Program on the formation of firms. The dependent variable is the city-level number of newly-registered firms with registered capital less than 2 million yuan, normalized by the local residence. Panel A presents estimations under the unconditional parallel trends assumption, while panel B allows conditional parallel trends with control variables including the pre-treatment value of population growth, saving rate, and human capita. Pre-trend test p-values are 0.001 and 0.128 for the two panels respectively. The row "TWFE" presents the coefficient on the treatment dummy in the two-way fixed effects regression. The row "Simple Weighted Average" presents the weighted average of all group-time ATE. The row "Cohort-Specific Effects" reports the ATE for the three cohorts of Broadband China Pilot Cities; here, g indexes the year that a city is first designated as "Broadband China Pilot City". The row "Calendar Time Effects" presents ATE by calendar year; here, t indexes the year. The row "Event Study" reports ATE by the length of exposure to the Broadband China Pilot City Program; here, e indexes the length of exposure to the Broadband China Pilot City Program. The column "Single Parameters" presents the further aggregation of each type of parameter.

Table 8: Mechanism: Broadband China ATE on innovation

Panel A: under the unconditional parallel trend assumption							
	Aggregated Effect	Partially Aggregated Parameter					
TWFE	0.118***						
	(0.041)						
Simple Average	0.139**						
	(0.055)						
Cohort-Specific Effect		g=2014	g=2015	g=2016			
	0.128**	0.210*	0.132*	0.037			
	(0.052)	(0.115)	(0.072)	(0.072)			
Calendar Year Effect		t=2014	t=2015	t=2016	t=2017	t=2018	t=2019
	0.144**	0.135	0.247***	0.146**	0.162**	0.057	0.118
	(0.060)	(0.134)	(0.067)	(0.071)	(0.064)	(0.072)	(0.092)
Event Study		e=0	e=1	e=2	e=3	e=4	e=5
	0.141**	0.140***	0.160***	0.099	0.159**	0.124	0.163
	(0.063)	(0.051)	(0.052)	(0.064)	(0.064)	(0.080)	(0.140)
Panel B: under the conditional parallel trend assumption							
	Aggregated Effect	Partially Aggregated Parameter					
TWFE	0.098**						
	(0.042)						
Simple Average	0.074*						
	(0.041)						
Cohort-Specific Effect		g=2014	g=2015	g=2016			
	0.072*	0.061	0.117**	0.038			
	(0.038)	(0.075)	(0.054)	(0.064)			
Calendar Year Effect		t=2014	t=2015	t=2016	t=2017	t=2018	t=2019
	0.061	-0.066	0.126**	0.038	0.100**	0.068	0.104**
	(0.041)	(0.085)	(0.063)	(0.065)	(0.049)	(0.055)	(0.052)
Event Study		e=0	e=1	e=2	e=3	e=4	e=5
	0.076*	0.042	0.076	0.011	0.135***	0.116**	0.077
	(0.044)	(0.044)	(0.047)	(0.056)	(0.050)	(0.055)	(0.090)

Notes: 1. Bootstrapped standard errors clustered at the city level are reported in parentheses.
2. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.
3. The layout is the same as Table 7. This table reports the effects of the Broadband China Pilot City Program on innovation. The dependent variable is the growth rate of the granted invention patents per 100 residence. Panel A presents estimations under the unconditional parallel trends assumption, while panel B allows conditional parallel trends with control variables including the pre-treatment value of saving rate growth, human capital growth, and the logarithm of GDP per capita. Pre-trend test p-values are 0.042 and 0.483 for the two panels respectively.

Table 9: Cross-validation: Broadband China ATE on broadband penetration growth and GDP per capita growth

Panel A: Broadband China ATE on broadband penetration growth							
	Aggregated Effect	Partially Aggregated Parameter					
TWFE with control	2.218*						
	(1.339)						
Simple Average	4.008*						
	(2.142)						
Cohort-Specific Effect		g=2014	g=2015	g=2016			
	3.478*	7.515*	2.870	-0.379			
	(2.004)	(4.186)	(1.963)	(3.396)			
Calendar Year Effect		t=2014	t=2015	t=2016	t=2017	t=2018	t=2019
	3.850*	3.917	1.316	5.975*	4.245	4.171	3.477
	(2.308)	(4.943)	(3.214)	(3.612)	(2.743)	(2.724)	(2.332)
Event Study		e=0	e=1	e=2	e=3	e=4	e=5
	4.761**	3.042	0.830	4.820*	3.721	6.750**	9.404*
	(2.325)	(2.424)	(2.477)	(2.829)	(2.406)	(2.924)	(4.831)
Panel B: Broadband China ATE on GDP per capita growth							
TWFE with control	0.573***						
	(0.166)						
Simple Average	0.809**						
	(0.358)						
Cohort-Specific Effect		g=2014	g=2015	g=2016			
	0.790**	0.871	0.917*	0.571			
	(0.331)	(0.431)	(0.404)	(0.540)			
Calendar Year Effect		t=2014	t=2015	t=2016	t=2017	t=2018	t=2019
	0.790**	0.410	1.238**	1.608**	0.410	0.472	0.597
	(0.351)	(0.409)	(0.506)	(0.658)	(0.332)	(0.323)	(0.350)
Event Study		e=0	e=1	e=2	e=3	e=4	e=5
	0.769**	0.938*	0.648	0.645	0.415	0.503	0.382
	(0.351)	(0.332)	(0.442)	(0.393)	(0.315)	(0.308)	(0.3817)

Notes: 1. Bootstrapped standard errors clustered at the city level are reported in parentheses.
2. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.
3. The layout is the same as Table 7. This table reports the effects of the Broadband China Pilot City Program on broadband penetration growth (Panel A) and GDP per capita growth (Panel B). Both panels are results under conditional parallel trends with control variables including the pre-treatment value of saving rate growth, human capital growth, and the logarithm of GDP per capita. Pre-trend test p-values are 0.653 and 0.207 for the two panels respectively.

Table 10: Long-difference: Broadband China and the digital adoption of firms

	(1) App	(2) Applet	(3) ICP	(4) Software	(5) Weibo	(6) Wechat
Panel A						
BC dummy	0.627***	0.403***	0.543***	0.790***	0.581***	0.374***
	(0.112)	(0.072)	(0.101)	(0.122)	(0.107)	(0.073)
Change in GDP	0.340***	0.128	-0.031	0.190	0.175	0.220***
	(0.125)	(0.084)	(0.120)	(0.136)	(0.120)	(0.084)
Change in residence	0.329**	0.354***	0.301**	0.525***	0.377**	0.223**
	(0.145)	(0.098)	(0.152)	(0.176)	(0.158)	(0.100)
Change in human capital	-0.058	0.001	-0.063	-0.069	-0.051	-0.007
	(0.058)	(0.038)	(0.046)	(0.064)	(0.053)	(0.039)
Constant	0.524	1.850***	1.444	1.678	1.745*	2.843***
	(0.974)	(0.657)	(0.941)	(1.062)	(0.939)	(0.655)
Observations	283	283	283	283	283	283
R-squared	0.170	0.161	0.139	0.198	0.148	0.142
Panel B						
BC order	0.357***	0.228***	0.299***	0.435***	0.329***	0.214***
	(0.053)	(0.033)	(0.045)	(0.053)	(0.050)	(0.034)
Change in GDP	0.373***	0.149*	-0.003	0.231*	0.205*	0.240***
	(0.124)	(0.083)	(0.119)	(0.132)	(0.119)	(0.082)
Change in residence	0.303**	0.337***	0.280*	0.494***	0.354**	0.208**
	(0.139)	(0.095)	(0.149)	(0.170)	(0.155)	(0.097)
Change in human capital	-0.031	0.018	-0.040	-0.036	-0.026	0.009
	(0.056)	(0.037)	(0.046)	(0.062)	(0.051)	(0.037)
Constant	0.760	2.003***	1.651*	1.979*	1.964**	2.984***
	(0.968)	(0.647)	(0.937)	(1.031)	(0.933)	(0.644)
Observations	283	283	283	283	283	283
R-squared	0.241	0.228	0.192	0.271	0.210	0.206

Notes: 1. Robust standard errors are reported in parentheses.
2. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.
3. Panel A is the long-difference regression with the key independent variable BC_1, or BC dummy, i.e., the dummy variable indicating whether a city participated in the Broadband China Pilot City Program. And the key independent variable is BC_2, or BC order, in Panel B is an ordered indicator with value of 0, 1, 2, and 3 if the city never participated in the program, participated in the last batch (the year 2016), the second batch (the year 2015), and the first batch (the year 2014), respectively.

Appendix

Table A1: Robustness check: OLS and IV results of the level model with two-way fixed effect

Dep: GDP per capita growth	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) IV
Lag of ln broadband penetration growth	0.417***	0.412***	0.115***	0.098***	0.140***
	(0.014)	(0.015)	(0.016)	(0.016)	(0.025)
Saving rate	0.159***	0.179***	0.145***	0.163***	0.154***
	(0.019)	(0.020)	(0.021)	(0.021)	(0.009)
Human capital	0.153***	0.137***	0.108***	0.066*	0.053***
	(0.035)	(0.046)	(0.034)	(0.037)	(0.014)
population growth	-0.006***	-0.007***	-0.002***	-0.003***	-0.003***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
ln GDP per capita in 2005	8.728***	8.595***	9.289***	9.080***	10.318***
	(0.199)	(0.256)	(0.187)	(0.195)	(0.145)
City FE	NO	YES	NO	YES	YES
Year FE	NO	NO	YES	YES	YES
Observations	2,140	2,140	2,140	2,140	2,140
R-squared	0.554	0.825	0.372	0.918	0.982

Notes: 1. Clustered (at city level) robust standard errors are reported in parentheses.
2. $***$ indicates $p < 0.01$; $**$ indicates $p < 0.05$; $*$ indicates $p < 0.1$.
3. Column (1) to (4) are OLS results, while column (5) is the IV result with the historical and topographical IVs. The first-stage F statistics is 112.106 with p-value 0.000. The overidentification test p-value is 0.63.

Table A2: Robustness: other measures of digital exposure growth and GDP per capita growth (OLS)

Dep: GDP per capita growth	(1) Baseline	(2) No control, full sample	(3) No control	(4) Baseline	(5) No control, full sample	(6) No control	(7) Baseline	(8) No control, full sample	(9) No control
Lag of broadband penetration growth another measure	0.043***	0.023***	0.030***						
	(0.008)	(0.007)	(0.007)						
Lag of mobile phone penetration growth				0.077***	0.093***	0.086***			
				(0.015)	(0.015)	(0.015)			
Lag of per capita telecommunication revenue growth							0.046***	0.065***	0.056***
							(0.007)	(0.008)	(0.008)
Saving rate growth	0.131***			0.122***			0.123***		
	(0.014)			(0.014)			(0.014)		
Human capital growth	0.033***			0.024***			0.035***		
	(0.009)			(0.009)			(0.009)		
First-difference of population growth	-0.308***			-0.320***			-0.223***		
	(0.030)			(0.031)			(0.026)		
Logarithm of GDP per capita in 2005	-1.306***	-1.977***	-1.893***	-1.284***	-1.797***	-1.703***	-1.302***	-1.817***	-1.763***
	(0.174)	(0.147)	(0.174)	(0.175)	(0.153)	(0.180)	(0.176)	(0.145)	(0.173)
Constant	19.324***	25.995***	25.573***	19.032***	23.761***	23.335***	19.993***	24.932***	24.824***
	(1.696)	(1.402)	(1.649)	(1.693)	(1.495)	(1.726)	(1.670)	(1.363)	(1.626)
Observations	2,608	3,188	2,608	2,608	3,240	2,608	2,792	3,365	2,792
R-squared	0.222	0.039	0.047	0.245	0.079	0.088	0.214	0.069	0.067

Notes: 1. Clustered (at city level) robust standard errors are reported in parentheses.

2. $***$ indicates $p < 0.01$; $**$ indicates $p < 0.05$; $*$ indicates $p < 0.1$.

3. In column (1)-(3), we use the usual residence instead of usual household to normalize the broadband subscribers. Column (4) to (6) use the mobile phone penetration rate as a proxy of digital exposure. And column (7) to (9) utilized the per capita telecommunication revenue to reflect the level of digital exposure.

Table A3: Robustness: other measures of digital exposure growth and GDP per capita growth (3G4G)

Dep: GDP per capita growth	(1) Before 3G: 2006-2009	(2) 3G-4G: 2010-2014	(3) After 4G: 2015-2019	(4) Before 3G: 2006-2009	(5) 3G-4G: 2010-2014	(6) After 4G: 2015-2019	(7) Before 3G: 2006-2009	(8) 3G-4G: 2010-2014	(9) After 4G: 2015-2019
Lag of broadband penetration growth another measure	0.004	0.032***	0.042***						
	(0.012)	(0.007)	(0.014)						
Lag of mobile phone penetration growth				0.014	0.036**	0.118***			
				(0.014)	(0.014)	(0.032)			
Lag of per capita telecommunication revenue growth							0.029***	0.032***	0.036**
							(0.009)	(0.010)	(0.017)
Controls	YES	YES	YES	YES	YES	YES	YES	YES	YES
Observations	680	899	1,029	680	1,132	796	903	1,135	754
R-squared	0.127	0.186	0.231	0.128	0.159	0.235	0.124	0.153	0.231

Notes: 1. Clustered (at city level) robust standard errors are reported in parentheses.

2. $***$ indicates $p < 0.01$; $**$ indicates $p < 0.05$; $*$ indicates $p < 0.1$.

3. The definitions of the key independent variables are the same as Table A2. The layout is the same as Table 3 for each three columns.

Table A4: Robustness test: other measures of digital exposure growth and GDP per capita growth (IV)

Dep: GDP per capita growth	(1) Historical IV	(2) Topographical IV	(3) Both IVs	(4) Historical IV	(5) Topographical IV	(6) Both IVs	(7) Historical IV	(8) Topographical IV	(9) Both IVs
Panel A									
Lag of broadband penetration growth another measure	0.174***	0.235***	0.183***						
	(0.041)	(0.061)	(0.039)						
Lag of mobile phone penetration growth				0.319***	0.374***	0.318***			
				(0.021)	(0.052)	(0.021)			
Lag of per capita telecommunication revenue growth							0.192**	0.258***	0.218***
							(0.076)	(0.084)	(0.069)
Saving rate growth	0.145***	0.146***	0.145***	0.112***	0.108***	0.113***	0.128***	0.126***	0.127***
	(0.015)	(0.015)	(0.015)	(0.015)	(0.015)	(0.015)	(0.016)	(0.016)	(0.016)
Human capital growth	0.034***	0.032**	0.034***	-0.004	-0.012	-0.004	0.039***	0.035**	0.037***
	(0.013)	(0.014)	(0.013)	(0.012)	(0.015)	(0.012)	(0.014)	(0.016)	(0.014)
First-difference of population growth	-0.395***	-0.429***	-0.400***	-0.449***	-0.475***	-0.449***	-0.181***	-0.159***	-0.172***
	(0.057)	(0.062)	(0.056)	(0.059)	(0.069)	(0.059)	(0.048)	(0.050)	(0.047)
Logarithm of GDP per capita in 2005	-0.636**	-0.290	-0.580**	-0.462**	-0.268	-0.467**	-0.844**	-0.603	-0.749**
	(0.303)	(0.385)	(0.289)	(0.231)	(0.278)	(0.232)	(0.345)	(0.385)	(0.331)
Constant	11.004***	6.813	10.331***	8.873***	6.512**	8.927***	14.759***	12.108***	13.710***
	(3.355)	(4.465)	(3.182)	(2.233)	(2.945)	(2.238)	(3.595)	(4.020)	(3.415)
Overidentification p-value			0.248			0.171			0.314
Observations	2,090	2,090	2,090	2,090	2,090	2,090	2,227	2,227	2,227
Panel B									
Historical IV * Broadband another measure	8.294***		7.476***						
	(0.808)		(0.809)						
Topographical IV * Broadband another measure		-10.442***	-5.054***						
		(1.697)	(1.685)						
Historical IV * Mobile phone				11.297***		11.580***			
				(0.476)		(0.682)			
Topographical IV * Mobile phone					-14.821***	1.695			
					(1.711)	(2.211)			
Historical IV * Telecommunication revenue							4.398***		3.129**
							(1.094)		(1.386)
Topographical IV * Telecommunication revenue								-13.371***	-7.477*
								(3.375)	(4.281)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Kleibergen-Paap rk Wald F statistics	89.158	46.728	46.812	535.343	106.792	277.321	13.160	19.813	12.485
Observations	2,090	2,090	2,090	2,090	2,090	2,090	2,227	2,227	2,227
R-squared	0.099	0.069	0.102	0.224	0.091	0.225	0.032	0.031	0.033

Notes: 1. Clustered (at city level) robust standard errors are reported in parentheses.
2. $***$ indicates $p < 0.01$; $**$ indicates $p < 0.05$; $*$ indicates $p < 0.1$.
3. The definitions of the key independent variables are the same as Table A2. The layout is the same as Table 4 for each three columns.

Table A5: Robustness test: screened samples (IV)

Dep: GDP per capita growth	(1) Exclude BSG	(2) Exclude BSG	(3) Exclude BSG	(4) Exclude BSG	(5) Exclude 8 nodals	(6) Exclude 8 nodals	(7) Exclude 8 nodals	(8) Exclude 8 nodals
Panel A								
Lag of broadband penetration growth	0.165***				0.165***			
	(0.038)				(0.039)			
Lag of broadband penetration growth another measure		0.187***				0.188***		
		(0.039)				(0.040)		
Lag of mobile phone penetration growth			0.318***				0.320***	
			(0.021)				(0.021)	
Lag of per capita telecommunication revenue growth				0.229***				0.211***
				(0.074)				(0.071)
Saving rate growth	0.145***	0.145***	0.113***	0.127***	0.147***	0.146***	0.113***	0.128***
	(0.016)	(0.015)	(0.015)	(0.016)	(0.016)	(0.016)	(0.015)	(0.017)
Human capital growth	0.037***	0.034**	-0.004	0.036**	0.037***	0.035***	-0.003	0.039***
	(0.013)	(0.013)	(0.012)	(0.014)	(0.013)	(0.013)	(0.012)	(0.014)
First-difference of population growth	-0.391***	-0.403***	-0.454***	-0.179***	-0.394***	-0.406***	-0.457***	-0.188***
	(0.056)	(0.056)	(0.060)	(0.049)	(0.057)	(0.058)	(0.061)	(0.049)
Logarithm of GDP per capita in 2005	-0.714**	-0.577*	-0.446*	-0.673*	-0.791***	-0.649**	-0.501**	-0.797**
	(0.286)	(0.295)	(0.247)	(0.350)	(0.290)	(0.300)	(0.254)	(0.341)
Constant	11.956***	10.244***	8.735***	12.939***	12.617***	10.844***	9.203***	14.161***
	(3.108)	(3.218)	(2.372)	(3.604)	(3.148)	(3.274)	(2.425)	(3.500)
Overidentification p-value	0.370	0.355	0.278	0.453	0.433	0.408	0.325	0.398
Observations	2,055	2,055	2,055	2,189	2,016	2,016	2,016	2,146
Panel B								
Historical IV * Broadband	7.245***				12.105***			
	(0.833)				(1.507)			
Topographical IV * Broadband	-5.906***				-7.132***			
	(1.775)				(1.742)			
Historical IV * Broadband another measure		7.652***				12.555***		
		(0.823)				(1.481)		
Topographical IV * Broadband another measure		-4.929***				-6.225***		
		(1.716)				(1.691)		
Historical IV * Mobile phone			11.871***				20.762***	
			(0.697)				(1.460)	
Topographical IV * Mobile phone			1.703				-1.237	
			(2.265)				(2.218)	
Historical IV * Telecommunication revenue				2.947**				6.469**
				(1.416)				(2.829)
Topographical IV * Telecommunication revenue				-7.125*				-7.653*
				(4.161)				(4.214)
Kleibergen-Paap rk Wald F statistics	47.496	48.596	309.121	11.207	46.631	47.440	316.511	11.432
Observations	2,055	2,055	2,055	2,189	2,090	2,090	2,090	2,227
R-squared	0.095	0.098	0.226	0.031	0.094	0.096	0.198	0.034

Notes: 1. Clustered (at city level) robust standard errors are reported in parentheses.
2. $***$ indicates $p < 0.01$; $**$ indicates $p < 0.05$; $*$ indicates $p < 0.1$.
3. Columns (1)-(4) use the sample that excludes Beijing, Shanghai, and Guangzhou as these three cities are the access points to the world's Internet backbone; and columns (5)-(8) exclude the eight nodal cities (Beijing, Shanghai, Guangzhou, Shenyang, Nanjing, Wuhan, Chengdu, and Xi'an) of the CHINANET.

Table A6: Robustness check: IV results with historical post office IV and topographical IV

Dep: GDP per capita growth	(1)	(2)	(3)	(4)
Panel A				
Lag of broadband penetration growth	0.185***			
	(0.040)			
Lag of broadband penetration growth another measure		0.208***		
		(0.041)		
Lag of mobile phone penetration growth			0.341***	
			(0.024)	
Lag of per capita telecommunication revenue growth				0.256***
				(0.074)
Saving rate growth	0.146***	0.146***	0.111***	0.126***
	(0.015)	(0.015)	(0.015)	(0.016)
Human capital growth	0.036***	0.033**	-0.008	0.035**
	(0.013)	(0.014)	(0.013)	(0.015)
First-difference of population growth	-0.402***	-0.414***	-0.460***	-0.160***
	(0.056)	(0.056)	(0.061)	(0.049)
Logarithm of GDP per capita in 2005	-0.592**	-0.442	-0.383	-0.612*
	(0.283)	(0.295)	(0.237)	(0.351)
Constant	10.509***	8.653***	7.908***	12.204***
	(3.122)	(3.270)	(2.304)	(3.623)
Overidentification p-value	0.609	0.575	0.503	0.961
Observations	2,090	2,090	2,090	2,227
Panel B				
Historical IV * Broadband	12.105***			
	(1.507)			
Topographical IV * Broadband	-7.132***			
	(1.742)			
Historical IV * Broadband another measure		12.555***		
		(1.481)		
Topographical IV * Broadband another measure		-6.225***		
		(1.691)		
Historical IV * Mobile phone			20.762***	
			(1.460)	
Topographical IV * Mobile phone			-1.237	
			(2.218)	
Historical IV * Telecommunication revenue				6.469**
				(2.829)
Topographical IV * Telecommunication revenue				-7.653*
				(4.214)
Kleibergen-Paap rk Wald F statistics	47.804	47.173	207.668	11.179
Observations	2,090	2,090	2,090	2,227
R-squared	0.094	0.096	0.198	0.034

Notes: 1. Clustered (at city level) robust standard errors are reported in parentheses.
2. $***$ indicates $p < 0.01$; $**$ indicates $p < 0.05$; $*$ indicates $p < 0.1$.
3. The historical IV is the number of post office in 1984.

Table A7: Robustness check: IV results with historical telecommunication revenue IV and topographical IV

Dep: GDP per capita growth	(1)	(2)	(3)	(4)
Panel A				
Lag of broadband penetration growth	0.173***			
	(0.039)			
Lag of broadband penetration growth another measure		0.197***		
		(0.041)		
Lag of mobile phone penetration growth			0.322***	
			(0.022)	
Lag of per capita telecommunication revenue growth				0.221***
				(0.069)
Saving rate growth	0.145***	0.145***	0.112***	0.127***
	(0.015)	(0.015)	(0.015)	(0.016)
Human capital growth	0.036***	0.034**	-0.005	0.037***
	(0.013)	(0.013)	(0.012)	(0.014)
First-difference of population growth	-0.395***	-0.408***	-0.451***	-0.171***
	(0.056)	(0.056)	(0.060)	(0.047)
Logarithm of GDP per capita in 2005	-0.656**	-0.504*	-0.451*	-0.737**
	(0.285)	(0.296)	(0.232)	(0.330)
Constant	11.284***	9.400***	8.743***	13.580***
	(3.134)	(3.272)	(2.248)	(3.403)
Overidentification p-value	0.433	0.430	0.279	0.424
Observations	2,090	2,090	2,090	2,227
Panel B				
Historical IV * Broadband	9.612***			
	(1.173)			
Topographical IV * Broadband	-6.387***			
	(1.738)			
Historical IV * Broadband another measure		10.086***		
		(1.159)		
Topographical IV * Broadband another measure		-5.451***		
		(1.683)		
Historical IV * Mobile phone			16.544***	
			(1.034)	
Topographical IV * Mobile phone			1.240	
			(2.247)	
Historical IV * Telecommunication revenue				4.700**
				(2.018)
Topographical IV * Telecommunication revenue				-7.318*
				(4.264)
Kleibergen-Paap rk Wald F statistics	44.913	44.900	289.604	11.438
Observations	2,090	2,090	2,090	2,227
R-squared	0.096	0.098	0.218	0.034

Notes: 1. Clustered (at city level) robust standard errors are reported in parentheses.
2. $***$ indicates $p < 0.01$; $**$ indicates $p < 0.05$; $*$ indicates $p < 0.1$.
3. The historical IV is the telecommunication revenue in 1984.

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