Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.

Telematics and Informatics 58 (2021) 101533

Contents lists available at ScienceDirect

Telematics and Informatics

journal homepage: www.elsevier.com/locate/tele

Broadband and economic growth in China: An empirical study during the COVID-19 pandemic period

Xiaoqun Zhang

Department of Media Arts, University of North Texas, 1155 Union Circle #310589, Denton, TX 76203-5017, United States

ARTICLE INFO

Keywords:
Broadband
Economic growth
Human capital
COVID-19
China

ABSTRACT

This paper proposed an economic model that describes the special role of broadband in the economic growth during the COVID-19 pandemic period. Empirical research was conducted using the data of China to investigate how broadband affected China's economic growth during this period. The findings showed broadband alleviated China's economic losses during the first a few months of 2020 when the new coronavirus spread across the country, and broadband affected China's economic growth to a larger extent during this pandemic period than during the normal time periods. These findings have policy implications for China as well as other countries where the pandemic is still pervasive.

1. Introduction

Broadband (high-speed Internet) has achieved rapid diffusion across the world during the past decades. There are multiple technological platforms, such as DSL, fiber-optics, powerline and cable; fixed wireless access, encompassing WiFi and WiMax, through which broadband services can be delivered. Organization for Economic Co-operation and Development (OECD) (2012) categorized these multiple platforms into two categories: fixed broadband and mobile broadband. International Telecommunication Union (ITU, 2019) showed that fixed broadband subscriptions have grown steadily during the past 15 years, and the global penetration level of fixed broadband was 14.9% in 2019. In the meantime, mobile broadband subscriptions have grown much faster, and the global penetration level of mobile broadband reached 83% in 2019.

With the rapid diffusion of broadband in many countries, people's demands for interactive media services, such as social media and streaming media have been boosted. And these strong demands spur social and streaming media industries. Several companies, such as Facebook, Twitter, Instagram, WhatsApp, WeChat, YouTube and TikTok, gained billions of users in short time periods and built their global networks. These companies not only transformed media industries to a great extent, but also changed the landscapes of Internet economy as well as the national economy. ITU (2003) argued broadband plays a significant role in an economy because it encourages innovation, increases productivity, and attracts foreign investment. As the Internet has become integrated with other industries more in-depth, the influence of broadband on national economy is more profound than ever before.

During the COVID-19 pandemic period, broadband plays a special role in national economy because the "working from home" mode via broadband has been adopted in many countries. This pandemic has caused huge economic damages in many countries. International Monetary Fund (IMF) (2020) stated that this pandemic has pushed the world into a recession, and it will be worse than the global financial crisis of 2008. China's economy shrank by 6.8% in the first three month of 2020, and suffered its first contraction in 28 years (Nagarajan, 2020). Notwithstanding, broadband helps economies alleviate the economic losses. While many cities in China

E-mail address: Xiaoqun.Zhang@unt.edu.

https://doi.org/10.1016/j.tele.2020.101533
Received 31 May 2020; Received in revised form 16 September 2020; Accepted 10 November 2020
Available online 16 November 2020
0736-5853/© 2020 Elsevier Ltd. All rights reserved.

implemented "stay at home" order and strict quarantine practices to prevent the spread of the coronavirus, a big number of firms as well as other organizations have been operating with the assistance of broadband. In June 2019, the number of machine to machine (M2M) connections, which is a measure of Internet of Things (IOT) in enterprises, reached 830 million with an annual growth rate 72% (China Academy of Information and Communications Technology, 2019). The rapid diffusion of M2M enables millions of people to work from home via broadband.

The purpose of this study is to estimate the influence of broadband on China's economic growth during the COVID-19 pandemic period. Although there are many empirical studies demonstrating broadband has positive impacts on economic growth across countries in general and in China in particular (e.g., Gruber et al., 2014; Ghosh, 2017; Hang and Zhu, 2014; Koutroumpis, 2009; Kumar et al., 2016), this study provides an investigation to explore the special role of broadband in China's economic growth during this unique public health crisis period.

2. Literature review

2.1. Broadband diffusion and digital divide

Broadband and its services are the outputs of many innovations in information and communication technologies (ICTs). These innovations have been diffused rapidly across the world over the past decades. However, there are discrepancies in the diffusion rates of these ICTs. The gap between the adoption rates of ICTs measures the digital divide, which was defined as the gap between the people who have access to ICTs and those who have not (Organization for Economic Co-operation and Development (OECD), 2001). Broadband is the most important ICTs in the contemporary society. Many popular applications such as social media, streaming media, and mobile apps must be performed via high-speed Internet. The same as other ICTs, there are also the gaps of broadband adoption rates across countries and within countries. The International Telecommunication Union (n.d.) reported that the average penetration rate (subscriptions per 100 people) of fixed broadband worldwide was 14.15% in 2018, rich countries had much higher penetration rates (e.g., European countries had the average penetration rate 30.2%) than poor countries (e.g., African countries had the average penetration rate 0.43%).

Many studies in the literature explored the factors that influence the digital divide. Multiple factors have been identified as the determinants, such as population and population density (e.g., Bagchi, 2005), education (e.g., Kiiski and Pohjola, 2002), economic openness (e.g., Yang and Shanahan, 2003), ICT price (e.g., Lee et al., 2017), platform competition (e.g., Bohlin et al., 2010), infrastructure investment (e.g., Billon et al., 2009), social media (e.g., Lee et al., 2017), and regulation (e.g., Kiiski and Pohjola, 2002). Among all the factors investigated, income level has been demonstrated as the most significant variable that drives the digital divide. There are multiple studies that provided the evidence using either the across countries data or the data within a country (e.g., Bagchi, 2005; Billon et al., 2009; Chinn and Fairlie, 2007; Funchs, 2009; Kiiski and Pohjola, 2002; Yamakawa et al., 2013).

There are also multiple studies that investigated the digital divide and broadband diffusion in China. Jing (2006) found that although China achieved fast diffusion of ICTs, there was a big digital divide between China and the major developed countries in the 1990s. It also revealed the digital divide existed among different areas of China. Harwit (2004) concluded that China made a big progress in the telephone and Internet diffusion, but the digital divide existed among regions with different income levels. Song et al. (2020) found an enormous spatial gap in terms of the compound ICT index values among many cities, and the income level is one of the major determinants of this digital divide.

2.2. Broadband and economic growth

The empirical research of the digital divide shows there is a positive correlation between broadband penetration and income level. This correlation can be interpreted from a consumption perspective. Zhang (2013), for example, proposed an Internet consumption model to illustrate this mechanism. It can also be interpreted from a production perspective. Haller and Lyons (2019), for example, argued broadband affects total factor productivity (TFP), which was defined as the portion of economic growth that is not explained by the labor and capital used in production (Solow, 1956). In other words, broadband is demonstrated as a crucial factor that affects economic growth besides labor and capital. There is also an argument that broadband helps build workers' skills and promote the accumulation of human capital (Akerman et al., 2015).

The positive influence of broadband on economic growth has been verified by many research projects at the country level. For example, Koutroumpis (2009) examined the relationship between broadband penetration and GDP growth for 22 OECD countries. Likewise, Gruber et al. (2014) estimated the impact of broadband access on GDP growth in 27 European Union member states. Ghosh (2017) did similar research for Middle East and North Africa (MENA) countries. There are also other studies that were conducted at the regional level. For example, Crandall et al. (2006) conducted research using the data of 48 states in the United States. Jung and Lopez-Bazoc (2020) conducted research using the data from the 27 Brazilian states. The positive influence of broadband on productivity has been investigated at the firm level. For example, Haller and Lyons (2019) examined whether the introduction of broadband services increased the firm productivity by using the data from 27,926 firms in Ireland. Farooqui and vanLeeuwen (2008) conducted similar research using the firm data in the manufacturing and services sectors of Netherlands and United Kingdom.

Many of these empirical studies found broadband has significant impacts on economic growth or productivity, especially at the country level and regional level. However, they reached inconsistent estimations on the extents of the influence of broadband on economic growth or productivity. For example, Czernich et al. (2011) found that a 10% increase in broadband penetration contributed to 0.9–1.5% in GDP growth. Meanwhile, Koutroumpis (2009) found a much lower influence: a 10% increase in broadband penetration

contributed to 0.25% in GDP growth. Jung and Lopez-Bazoc (2020) argued that the positive impact of broadband on productivity is also not uniform at the regional level. At the firm level, previous studies obtained even more diverse results. For example, Haller and Lyons (2019) found the positive and significant impact of broadband on firm's total factor productivity. However, Haller and Lyons (2015) did not find any statistically significant result regarding this relationship.

There are also multiple studies investigating the influence of broadband on China's economic growth. Using the longitudinal data, Kumar et al. (2016) estimated the contribution of ICT to China's economic growth over the period 1997–2013. This study found that 10% increase of fixed broadband and mobile broadband penetration increased the productivity by 0.11%. Other studies found the contribution of broadband to the economic growth is even larger. For example, Hang and Zhu (2014) showed that 10% increase of broadband penetration increased the productivity by 0.19% using the provincial data during 2000–2011. He et al. (2013) estimated 10% increase of broadband penetration increased the economic growth by 0.424% using the provincial data during 2001–2010. Chen et al. (2011) showed broadband had higher impacts on economic growth in less developed regions than in more developed regions. For example, 10% increase of the optical fiber length per 100 people in Xijiang, which is an underdeveloped region in China, increased the GDP per capita growth by 0.102%. Meanwhile, 10% increase of the optical fiber length per 100 people in Chongqing, which is a developed region in China, increased the GDP per capita growth by 0.086%. Li and Wu (2020) argued that there is a threshold Internet penetration level above which broadband significantly promotes economic growth, and this threshold Internet penetration level is 7.72%.

2.3. Broadband and human capital

Broadband affects economic growth via multiple mechanisms. Scholars investigated these mechanisms from three major perspectives. The first perspective argues broadband is one type of technologies that affect both capital productivity and labor productivity, and is one component of TFP (e.g., Haller and Lyons, 2019). The second perspective believes that broadband consists of a specific capital that increases the amount of capital per labor, a process called capital deepening (e.g., Farooqui and vanLeeuwen, 2008). The third perspective holds broadband is the tool that helps people learn skills and knowledge, which are the essential parts of human capital (e.g., Akerman et al., 2015). During the COVID-19 pandemic period, many people adopted "working from home" mode because of the "stay at home" orders and quarantine practices. Therefore, the role of broadband in accumulating human capital becomes more prominent during this period.

Human capital represents the sets of skills and knowledge that help workers improve work efficiency and productivity (Becker, 1964). Education and health are believed to be the determinants of human capital (e.g., Becker, 2007; Lucas, 1988; Mankiw et al., 1992). ICTs especially computer and the Internet are also regarded as the tools that help people accumulate knowledge and skills, and they are widely used in formal education and informal education. Moreover, scholars found that ICTs have different impacts on different types of workers. Entorf and Kramarz (1998), for example, found computers help skilled workers much more than less skilled workers in production activities. Autor et al. (2003) argued ICTs have different impacts on different types of tasks. In particular, they argued that ICTs substitute for workers in performing routine tasks, which are repetitive and predictable tasks such as picking or sorting, repetitive assembly, record-keeping, and calculation; and complement workers in executing nonroutine tasks, which require for problem-solving and communications skills such as responding to discrepancies, improving production processes, and coordinating and managing the activities of others.

Scholars also conducted empirical research to investigate the specific effects of broadband on human capital accumulation. Akerman, Gaarder, and Mogstad (2015) found broadband improved the labor market outcomes and productivity of skilled workers, but had negative impacts on unskilled workers using the data of a sample of Norwegian firms over the period 2001–2007. There are many other empirical studies that demonstrated broadband had a positive impact on employment and labor market outcomes (e.g., Lehr et al., 2006; Crandall et al., 2006; Shideler et al., 2007; Thompson and Garbacz, 2008). These findings are further supported by a recent survey of 8672 adults in the United States during the COVID-19 pandemic period. This survey showed more people in the four income quintiles (second, middle, forth, and top) worked at home rather than were not able to work. In the top quintile, 71% of respondents worked at home, and only 19% respondents were unable to work (Reeves and Rothwell, 2020).

The knowledge and skills that affect productivity are not limited to the specific know-hows that are used directly in the production process. The majority of the knowledge disseminated through broadband and its supported streaming and social media platforms is not these specific know-hows. Nevertheless, the general knowledge people obtain from broadband is also crucial for their production activities. This type of knowledge is especially helpful for people to perform nonroutine tasks (Autor et al., 2003). It also helps people make wiser decisions in other activities, such as purchase, investment, health, and entertainment, which would increase their social welfare. Broadband also fundamentally transforms the landscape of education as remote/online education becomes a major education mode for both informal and formal education. The educative information as well as people's social interaction on broadband reinforce the ecology of education theory, which argues schooling is removing from the center of education, and education should be more appropriate to be a conceptualization of a variety of related institutional configurations of educative and social interactions (Cremin, 1976). These educative and social interactions include both the formal online/remote learning programs and courses, and the informal online learning activities.

3. Hypotheses and research question

Broadband has diffused rapidly in China during the past decades. Currently, China's broadband penetration level is much higher than the world average. China is the country where the COVID-19 first exploded, and where this pandemic has been quickly controlled

by the rigorous "stay at home" orders and quarantine practices. Thus, China becomes a unique case from which the role of broadband in economic growth during the pandemic period can be thoroughly investigated. The special role of broadband during the COVID-19 pandemic period is that it enabled millions of people to work at home, and thus, sustained production activities to a certain extent. In other words, broadband helped China alleviate economic losses during this period. Based on the literature review of broadband, human capital and economic growth, the following research hypotheses and question are proposed:

Hypothesis 1: Broadband penetration has a significant and positive correlation with China's economic growth during the period of COVID-19 pandemic controlling for other variables.

Research question: To what extent did broadband influence China's economic growth during the period of COVID-19 pandemic?

Hypothesis 2: The influence of broadband on economic growth in the period of COVID-19 pandemic is larger than that in the normal time.

4. Method and data

The production function used for the analysis is the Cobb-Douglas production function (Cobb and Douglas, 1928), which reflects the relationships between the inputs — physical capital and labor — and the amount of output produced.

$$Y = AK^{\alpha}L^{\beta} \tag{1}$$

where Y is output, K is physical capital, L is labor, A represents total factor productivity (TFP), α denotes the output elasticity for physical capital, β denotes the output elasticity for labor.

The economic growth rate function can be derived from the production Eq. (1):

$$\frac{\dot{Y}}{Y} = \frac{\dot{A}}{A} + \alpha\frac{\dot{K}}{K} + \beta\frac{\dot{L}}{L} \tag{2}$$

During the COVID-19 pandemic period, the number of workers engaged in production activities has been decreased rapidly due to the "stay at home" orders and quarantine practices in many places. These orders and practices were more strictly executed in the places where there were more COVID-19 cases. Thus, the number of workers engaged in production activities should be negatively associated with the number of COVID-19 cases. On the other hand, broadband enabled many people work from home. The number of workers engaged in production activities should be positively associated with broadband penetration rate. Based on these arguments, the following labor function is proposed:

$$L_t = e^{\ln[F(B)]-\ln[G(C)]}L_{t-1} \tag{3}$$

Where L_t is the number of workers engaged in production during the period COVID-19 pandemic period. L_{t-1} is the number of workers before the COVID-19 pandemic period. B represents the broadband penetration rate; F(B) denotes the impact of broadband on the number of workers engaged in production activities. C represents the number of COVID-19 cases; G(C) denotes the impact of the COVID-19 pandemic on the number of workers engaged in production.

As previous studies demonstrated the digital divide exists among different regions of China (e.g., Song et al., 2020), Eq. (3) describes how the digital divide affects the number of workers engaged in production during the COVID-19 period in different regions. In particular, this equation shows the higher broadband penetration a region has, the larger number of workers are engaged in production activities, and vice versa.

The following labor growth function can be derived from the Eq. (3)

$$\frac{\dot{L}_t}{L_t} = \frac{\dot{F}(B)}{F(B)} - \frac{\dot{G}(C)}{G(C)} + \frac{\dot{L}_{t-1}}{L_{t-1}} \tag{4}$$

Combining Eqs. (2) and (4), the following economic growth function can be derived:

$$\frac{\dot{Y}}{Y} = \frac{\dot{A}}{A} + \alpha\frac{\dot{K}_t}{K_t} + \beta\frac{\dot{L}_{t-1}}{L_{t-1}} + \beta\frac{\dot{F}(B)}{F(B)} - \beta\frac{\dot{G}(C)}{G(C)} \tag{5}$$

Based on Eq. (5), the following linear regression model was used to estimate the influence of broadband on China's economic growth during the COVID-19 pandemic period.

$$GDPG_{i,t} = c + \alpha KGi_{,t} + \beta LG_{i,t-1} + \gamma BG_{i,t} - \delta CG_{i,t} + \mu_{i,t} \tag{6}$$

where $GDPG_{i,t}$ is the GDP growth rate during the COVID-19 period. $KGi_{,t}$ is the physical capital growth rate during the COVID-19 period. $LG_{i,t-1}$ is the labor growth rate during the period prior to the COVID-19 period. Suppose $BG_{i,t}$ is positively related to the broadband penetration growth rate during the COVID-19 period. Suppose $CG_{i,t}$ is positively correlated with the proportion of COVID-19 cases in the population during the COVID-19 period. c is the intercept, representing TFP growth rate. $\alpha, \beta, \gamma, \delta$ are the elasticity coefficients of physical capital growth rate, labor growth rate, broadband penetration growth rate, and the proportion of COVID-19 cases in the population. $\mu_{i,t}$ is the residue.i denotes the provincial district, $i = 1, 2, \cdots 31$.

To test the hypothesis 2, the influence of broadband on economic growth during the same time period in the year prior to 2020 was estimated. The regression model was modified into the following equation:

$$GDPG_{i,t} = c + \alpha KGi_{,t} + \beta LG_{i,t-1} + \gamma BG_{i,t} + \mu_{i,t} \quad (7)$$

The economic data of 31 provincial districts in mainland China data used in the analysis were obtained from the National Bureau of Statistics (n.d.), which is the authoritative government agency in China. It recently reported the economic data of March and April 2020 when the COVID-19 spread all over the country. The data of cumulative industrial value added were used to measure economic growth. The data of cumulative increase in fixed assets were used to measure capital growth rate. The data of employed persons in urban units were used to measure the number of workers in production activities. As the National Bureau of Statistics only reported the data of employed persons in urban units annually of these 31 provincial districts in 2018 and prior periods, the growth rate of labor was estimated using the data of 2018 and 2017. This is also the case for the broadband penetration data. The data of COVID-19 case were obtained from Tencent News website (Tencent, n.d.). To test the hypothesis 2, the data of cumulative industrial value added and the data of cumulative increase in fixed assets in March and April in 2019 were also obtained from the National Bureau of Statistics (n.d.).

5. Results

The regression analysis was performed for four time periods: March 2020, April 2020, March 2019, and April 2019. As GDP was measured by the cumulative industrial value added, the GDP growth rate in the period of March 2020 is the GDP growth rate of the first three months of 2020. This is the same for the tests of other periods. The regression estimate results were reported in Table 1.

Hypothesis 1 was proposed to testify whether broadband penetration has a significant and positive correlation with China's economic growth during the period of COVID-19 pandemic controlling for other variables. The results of Model 1 showed that broadband penetration growth rate has a significant and positive coefficient ($\gamma = .187, t = 2.893$) during the first three months of 2020. The results of Model 2 showed that broadband penetration rate has a significant and positive coefficient ($\gamma = .130, t = 3.016$) during the first four months of 2020. Other variables in the production function, e.g., physical capital growth rate ($KG_{(t)}$), labor growth rate ($LG_{(t-1)}$), and the proportion of COVID-19 cases in population ($CG_{(t)}$) were controlled for testing this hypothesis. All these results support hypothesis 1.

Model 1 also showed that the intercept is significantly and negatively correlated with GDP growth rate ($c = -9.807, t = -5.394$). The correlations between physical capital growth and GDP growth rate, and the correlations between labor growth rate and GDP growth rate are not significant. The coefficient of the proportion of COVID-19 cases in population is negative and significant ($\delta = -3.323, t = -5.641$). Model 2 showed that the intercept is also significantly and negatively correlated with GDP growth rate ($c = -5.597, t = -6.847$). The correlation between physical capital growth and GDP growth rate is significant and positive ($\alpha = .141, t = 2.225$). The correlation between labor growth rate and GDP growth rate is not significant. The coefficient of the proportion of COVID-19 cases in population is negative and significant ($\delta = -1.770, t = -4.299$).

The research question asks to what extent did broadband influence China's economic growth during the period of COVID-19 pandemic. The results of Model 1 showed the elasticity coefficient of broadband penetrate growth rate $\gamma = .187$. That means, 10% of the increase of broadband penetrate rate would result in 1.87% of GDP growth rate during the first three months of 2020. The results of Model 2 showed the elasticity coefficient of broadband penetrate growth rate $\gamma = .130$. That means, 10% of the increase of broadband penetrate rate would result in 1.30% of GDP growth rate during the first four months of 2020.

Hypothesis 2 tests whether the influence of broadband on economic growth in the period of COVID-19 pandemic is larger than that in the normal time. Regression Eq. (7) was used to estimate the impact of broadband growth rate on GDP growth rate during the first three and four months of 2019. The results of Model 3 and Model 4 showed broadband penetration growth rate has significant and positive coefficients ($\gamma = .082, t = 2.944$; $\gamma = .084, t = 2.174$). These results suggested that 10% of the increase of broadband penetrate rate would result in 0.82% of GDP growth rate during the first three months of 2019, and 0.84% of GDP growth rate during the first fourth months of 2019. Comparing the results of the same periods of 2020, it is obviously that the contribution of broadband to GDP growth during the period of COVID-19 pandemic is larger than that during the same time period of the previous year. This hypothesis is supported.

Table 1
Regression estimates for GDP growth using the data of 31 provincial districts.

	Model 1 (03/2020)	Model 2 (04/2020)	Model 3 (03/2019)	Model 4 (04/2019)
c	-9.807^{***} (-5.394)	-5.597^{***} (-6.847)	4.646^{***} (6.745)	4.283^{***} (4.660)
$KG_{(t)}$	0.021 (0.233)	0.141* (2.225)	0.080* (2.074)	0.049 (1.703)
$LG_{(t-1)}$	-0.061 (-0.568)	-0.055 (-0.662)	0.091 (1.479)	0.089 (1.501)
$BG_{(t)}$	0.187^{**} (2.893)	0.130^{**} (3.016)	0.082^{**} (2.944)	0.084* (2.174)
$CG_{(t)}$	-3.323^{***} (-5.641)	-1.770^{***} (-4.299)		
Adjusted R^2	0.958	0.960	0.194	0.138
F	170.4^{***}	181.5^{***}	3.410*	2.599

Note: $KG_{(t)}$ is the physical capital growth rate during the COVID-19 period. $LG_{(t-1)}$ is the labor growth rate during the period prior to the COVID-19 period. $BG_{(t)}$ is the broadband penetration growth rate during the COVID-19 period. $CG_{(t)}$ is the proportion of COVID-19 cases in the population during the COVID-19 period. c is the intercept. Number of observations = 31. Weighted least square regression was applied to reduce the heteroscedasticity effects.
* $p < .05$; ** $p < .01$; *** $p < .001$.

6. Conclusion and discussion

Broadband has been regarded as one of the driving forces of economic growth in the literature. This study furthers explored the role of broadband in China's economic growth during the period of COVID-19 pandemic. The findings have policy implications for China to sustain its economic growth. As China is the first major country where this pandemic exploded and the first major economy that recovered from it, this study also has implications for other countries where the pandemic is still pervasive.

The results of regression estimates showed that broadband penetration growth rate is significantly and positively correlated with GDP growth rate during the first three and four month of 2020. The COVID-19 pandemic was pervasive in China during these periods, and many regional governments executed "stay at home" orders and strict quarantine rules. At the same time, many organizations adopted "working from home" mode. Therefore, the role of broadband during this pandemic becomes more prominent than ever before as the broadband access is the necessity for the remote work performed online. Without broadband, this "working from home" mode would not be possible. In this regard, broadband plays a special role in human capital engaged in production during the pandemic period.

This study proposed an economic growth model that accommodates this special role of broadband in economic growth. In this model, the number of workers engaged in production activities is determined by three factors, the number of workers in the previous period, broadband penetration rate, and the COVID-19 cases. Broadband affected the number of workers in a positive way. That is, the higher level of broadband penetration, the more people can engage in production. This feature reflects the specific role of broadband during the COVID-19 pandemic period as many people used broadband to work at home. The proportion of COVID-19 cases in the population negatively affected the number of workers. The larger number of COVID-19 cases in the region, the more serious the pandemic was, the more rigorous "stay at home" orders and quarantine rules were executed, and then, the less people participated in production. The regression models are based on these arguments. The high adjusted R^2 values of Model 1 and Model 2 suggest the regression model predicts China's economic growth very well during the COVID-19 pandemic period.

This study also estimated the extent to which broadband contributed to the GDP growth during the COVID-19 pandemic period. The results showed 10% of the increase of broadband penetrate rate would result in 1.87% of GDP growth rate during the first three months of 2020, and 1.30% of GDP growth rate during the first fourth months of 2020. As the number of COVID-19 cases decreased rapidly in April 2020, the difference in the elasticity coefficients between March and April 2020 suggested that broadband had more influence on GDP growth when the pandemic was more severe. This conclusion is supported by the fact that many firms resumed work when the COVID-19 cases dropped quickly. When less people worked at home via broadband, the special role of broadband in sustaining human capital in production became less significant. The results also showed that the contribution of broadband to GDP growth is larger during the COVID-19 pandemic period than during the same period of the previous year. As many more people used broadband to work at home during the pandemic period than during the normal period, broadband indeed has more significant influence on productivity and economic growth during the pandemic period than during the normal period.

Hang and Zhu (2014) showed that 10% increase of broadband penetration increases GDP growth by 0.19% using the provincial data during 2000–2011. He et al. (2013) estimated 10% increase of broadband penetration increases the economic growth by 0.424% using the provincial data during 2001–2010. This study showed the contribution of broadband to GDP growth during the COVID-19 pandemic period is much higher than those of the previous estimations. Furthermore, the estimates of the same periods of 2019 are also much higher than the estimates in the previous studies. The higher contribution of broadband to GDP growth should attribute to the higher broadband penetration level. In 2011, China had 150 million broadband users, constituting 11.5% of total population. In 2019, this number increased to 449 million, constituting 32.1% of total population (National Bureau of Statistics (n.d.). Li and Wu (2020) argued that 7.72% is a threshold penetration level above which broadband significantly promotes economic growth. During the years before 2011, the broadband penetration rates in many places in China did not reach that threshold.

Although the broadband penetration rates of all these 31 provincial districts go far beyond the threshold, the digital divide exists among these regions. In 2018, the highest broadband penetration region is Zhejiang province (46.3%). The lowest broadband penetration region is Heilongjiang province (28.4%). This study demonstrated that broadband penetration growth rate had a positive correlation with economic growth rate during the COVID-19 period. That means, the regions with higher broadband penetration rates benefited more in terms of economic growth than the regions with lower broadband penetration rates. In this regard, the digital divide within China influenced the extents of the economic recovery of 31 provincial districts from the pandemic recession.

The significant contribution of broadband to GDP growth found in this study also relates to the externality of broadband network, which means that the value of the network for a user depends not only on his/her participation but also on the size of the network (Liebowitz and Margolis, 2002). Mayo and Wallsten (2011) argued that there are three different types of network effects: Subscriber effect, which means that the benefits to a society from the additional subscriber are larger than those of this subscriber. Ubiquity effect, which means that a user of a network obtains benefits that emanate from the geographic ubiquity of the network. Diversity effect, which means a network user obtains benefits from diverse consumption behaviors of other network users.

These three types of network effects occur when broadband is used to accumulate human capital. The subscriber effect takes place whenever a broadband user joins an online learning community/platform where he/she usually not only learns new knowledge but also shares his/her knowledge. Ubiquity effect takes place when a broadband user learns knowledge from other users around the world. The major social and streaming networks such as Facebook, Twitter, Instagram, WhatsApp, WeChat, YouTube and TikTok have become global networks through which users around the world share information and knowledge. Diversity effect also happens when broadband users exchange information and knowledge on the Internet with each other. The users can learn something new from these exchanges. Broadband enables the users from different parts of the world to build a global knowledge bank from which every user can learn new knowledge.

The results of this study also showed that the proportion of COVID-19 cases in the population significantly affected GDP growth during the pandemic period. The elasticity coefficient of this variable is significant and negative ($\delta = -3.323, t = -5.641$) during the first three months of 2020, and also significant and negative ($\delta = -1.770, t = -4.299$) during the first four months of 2020. That means, 10% of the increase of the proportion of COVID-19 cases in the population would result in 33.23% of GDP decrease during the first three months of 2020, and 17.70% of GDP decrease during the first four months of 2020. The proportion of COVID-19 cases in the population decreased rapidly in the March and became very low at the end of April 2020 (Tencent, n.d.). Many firms across China resumed work when the cases of COVID-19 dropped rapidly. As there were more firms resumed work in April than in March, the losses of China's economy in April are smaller than those in March.

Model 1 showed the physical capital variable ($KG_{(t)}$) did not affected the GDP growth significantly during the first three months of 2020. There were millions of firms that could not conduct production activities during this period. Although the physical capital was still there, it was not the input of production activities. The labor variable ($LG_{(t-1)}$) did not have significant coefficient in any of the four models. It might be the result of data manipulation. National Bureau of Statistics only reported the data of employed persons in urban units annually rather than monthly. The recent data reported are in the year 2018. The growth rate of labor was estimated using the data of 2018 and 2017, which would not be the accurate estimation of monthly data.

The estimates of the intercepts of these four models showed that they were negative and significant during the first three months (c = −9.807, t = −5.394) and the four months (c = −5.597, t = −6.847) of 2020; but were positive and significant during the first three months (c = 4.646, t = 6.745) and the four months (c = 4.283, t = 4.660) of 2019. The intercept represents the total factor productivity (TFP), which is the measure of all other exogenous factors that would affect GDP growth. These exogenous factors include multiple other factors that are not included in the production function, such as education, technological progress, public health, public policies, etc. As most of the facilities and institutions were not effectively functional during the pandemic period, the overall effect of all these exogenous factors should be negative. This is supported by the findings of this study. Although the strict "stay at home" and quarantine policies effectively alleviated the spread of the coronavirus across the country, they also restricted many activities that contribute to productivity. During the normal period, these exogenous factors affected China's economic growth positively as demonstrated by this study.

Overall, the findings of this study suggested that broadband helped China's economy recover from the COVID-19 pandemic. Broadband has diffused rapidly in China during the past decade when the number of broadband users expanded three times. In 2019, the broadband penetration reached 32.1% population (National Bureau of Statistics, n.d.), which is much higher than the world average level 14.5% (ITU, 2019). This rapid diffusion of broadband significantly contributed to China's economic growth during normal time, as demonstrated by many previous studies. This study showed that broadband affected China's economic growth to a larger extent during the COVID-19 pandemic period than during other normal periods.

These findings have implications for China's economy to further recover from the pandemic. Although there were a few new COVID-19 cases after April 2020, there is still a possibility of the second exploration in the future. If the vaccine cannot be produced in the short future or not effectively fight against the new coronavirus, many people could be infected and "stay at home" orders would be executed again. If this happens, "working from home" would still be a viable working mode to keep production continuing during the pandemic period. Broadband would be the necessity for such a remote working mode. Further promoting the diffusion of broadband in China would help China alleviate economic damages in the next pandemic explosion.

Although China has achieved a big progress in broadband diffusion, previous studies showed there are still big gaps in terms of broadband penetration between China and other major developed countries. The digital divide also exists within China, i.e., there are big gaps of broadband penetration between different areas of China. Chinese governments and telecommunication industry should formulate new strategies to bridge the digital divide between China and developed countries, and between different areas in China. As previous studies showed that infrastructure investment directly affects the digital divide besides other socioeconomic factors (Billon et al., 2009), Chinese governments should make policies that encourage the telecommunication infrastructure investment in the regions with low broadband penetration rates. Government subsidy and tax-cutting would be effective policy choices. The broadband penetration is also determined by the consumers' adoption behaviors, which are restricted by their purchase power (Zhang, 2013). Governments should also subsidize the adoption of broadband of consumers, as well as the public education institutions and libraries in these regions. The competition and regulations are also believed to influence the digital divide (Bohlin et al., 2010; Kiiski and Pohjola, 2002). Governments should apply regulations that ensure the competition in telecommunication industry. The full competition is crucial to maintain high quality services and fair prices. The next generation of mobile broadband, 5G, would be a new technology that helps China bridge the digital divide, as Chinese companies have gained leadership in some areas of this new technology.

The findings of this study also have implications for other countries where the COVID-19 is currently pervasive. Broadband should also play a significant role in these countries as "working from home" also became a major working mode. The economies with higher broadband penetration levels should benefit more from broadband than the economies with lower levels. Promoting broadband diffusion would be an effective strategy for these countries to reduce the economic losses during the current pandemic as well as the next exploration. In the United States, providing universal broadband service has become a major telecommunication policy motion at the national level and state level during the COVID-19 pandemic period (Eggerton, 2020; Killion, 2020).

Although the findings of this study are straightforward and have clear policy implications, it should be noted these findings suffer from the data limitations. In particular, the National Bureau of Statistics only reported the annual data of employed persons in urban units of the 31 provincial districts, and the most recent data are in the year 2018. This study estimated the growth rates of labor in March and April 2020 using the annual data in previous years. The data of the broadband penetration rates have the same problem. This would create inaccuracy in the measurement of these two variables. This is the major shortcoming of this study. Nevertheless, the employment rate and broadband adoption rate have kept relatively stable in recent years. The errors generated by the data

manipulation should not be very substantial. The R^2 values of Model 3 and Model 4 are low, showing the limitation of these models in explaining the GDP growth during normal periods.

Notwithstanding these limitations, the estimations of this study suggested the significant role of broadband in alleviating China's economic losses during the COVID-19 pandemic period. The findings have clear policy implications for China, as well as for other countries which are now suffering from the pandemic: promoting broadband diffusion would help their economies recover from the pandemic. Future research should investigate how broadband affected economic growth at the city or county level, and how broadband affected productivity at the firm level or household level during the pandemic period. The research in this direction will further explore the relationship between the digital divide and discrepancies of economic growth and productivity of different regions and entities during this devastating public health crisis period.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Akerman, A., Gaarder, I., Mogstad, M., 2015. The skill complementarity of broadband Internet. Q. J. Econ. 130 (4), 1781–1824.

Autor, D.H., Levy, F., Murnane, R.J., 2003. The skill content of recent technological change: an empirical exploration. Q. J. Econ. 118 (4), 1279–1333.

Bagchi, K., 2005. Factors contributing to global digital divide: Some empirical results. J. Global Inf. Technol. Manage. 8, 47–65.

Becker, G., 1964. Human Capital: A Theoretical and Empirical Analysis, with Special Reference to Education. Harvard University Press, Cambridge, MA.

Becker, S.G., 2007. Health as human capital: synthesis and extensions. Oxford Econ. Papers 59, 379–410.

Billon, M., Marco, R., Lera-Lopez, F., 2009. Disparities in ICT adoption: a multidimensional approach to study the cross-country digital divide. Telecommun. Policy 33, 596–610.

Bohlin, A., Gruber, H., Koutroumpis, P., 2010. Diffusion of new technology generations in mobile communications. Inf. Econ. Policy 22, 51–60.

China Academy of Information and Communications Technology. (October, 2019). White book on China Digital Economy Development. Retrieved from http://www.caict.ac.cn/kxyj/qwfb/bps/201910/P020191031512605025697.pdf.

Chen, L., Li, J., Xu, C., 2011. Xinxi jichu sheshi yu jingji zengzhang: Jiyu zhongguo shengji shuju fenxi. J. Manage. Sci. 23 (1), 98–107.

Chinn, M.D., Fairlie, R.W., 2007. The determinants of the global divide: A cross-country analysis of computer and internet penetration. Oxford Econ. Papers 59, 16–44.

Cobb, C.W., Douglas, P.H., 1928. A theory of production. Am. Econ. Rev. 18, 139–165.

Crandall, R., Lehr, W., & Litan, R (2006). The effects of broadband deployment on output and employment: A cross-sectional analysis of U.S. data. Issues in Economic Policy (Brookings Institution). Retrieved from https://www.brookings.edu/wp-content/uploads/2016/06/06labor_crandall.pdf.

Cremin, L.A., 1976. Public Education. Basic Books, New York.

Czernich, N., Falck, O., Kretschmer, T., Woessman, L., 2011. Broadband infrastructure and economic growth. Econ. J. 121, 505–532.

Eggerton, J. (April 6, 2020). Pandemic amplifies calls for universal broadband. Retrieved from https://www.multichannel.com/news/pandemic-amplifies-calls-for-universal-broadband.

Entorf, H., Kramarz, F., 1998. The impact of new technologies on wages: lessons from matching panels on employees and on their firms. Econ. Innov. New Technol. 5 (2–4), 165–198.

Farooqui, S. & vanLeeuwen, G. (2008). ICT investment and productivity. In Eurostat. (2008) Information society: ICT impact assessment by linking data from different sources (pp. 163–189). Retrieved from https://ec.europa.eu/eurostat/documents/341889/725524/2006-2008-ICT-IMPACTS-Summary-Report.pdf/511f221c-d4d7-4fb3-8558-dad771d8c7f3.

Funchs, C., 2009. The role of income inequality in a multivariate cross-national analysis of the digital divide. Soc. Sci. Comp. Rev. 27 (1), 41–58.

Ghosh, S., 2017. Broadband penetration and economic growth: do policies matter? Telematics Inform. 34, 676–693.

Gruber, H., Hätönen, J., Koutroumpis, P., 2014. Broadband access in the EU: an assessment of future economic benefits. Telecommun. Policy 38 (11), 1046–1058.

Haller, S.A., Lyons, S., 2015. Broadband adoption and firm productivity: evidence from Irish manufacturing firms. Telecommun. Policy 39 (1), 1–13.

Haller, S.A., Lyons, S., 2019. Effects of broadband availability on total factor productivity in service sector firms: evidence from Ireland. Telecommun. Policy 43 (1), 11–22.

Hang, B., Zhu, P., 2014. Kuandai dui Zhongguo jingji zengzhang yingxiang de shizheng fenxi. Statistical Res. 10, 49–54.

Harwit, E., 2004. Spreading telecommunications to developing areas in China: Telephones, the Internet and the digital divide. China Quarterly 180, 1010–1030.

He, Z., Wu, X., Chen, X., Lu, T., 2013. Kuandai dui woguo guoming jingji zengzhang de yingxiang. J. Beijing Univ. Posts Telecommun. (Social Sci. Edition) 1, 53–61.

International Monetary Fund (IMF) (April 6, 2020). An early view of the economic impact of the pandemic in 5 charts. Retrieved from https://blogs.imf.org/2020/04/06/an-early-view-of-the-economic-impact-of-the-pandemic-in-5-charts/.

International Telecommunication Union (ITU). (2019). Measuring digital development: Facts and figures 2019. Retrieved from https://www.itu.int/en/ITU-D/Statistics/Pages/facts/default.aspx.

International Telecommunication Union (ITU). (2003). The birth of broadband: ITU Internet reports, Geneva.

The International Telecommunication Union (n.d.). Fixed broadband. Retrieved from https://www.itu.int/net4/ITU-D/icteye/#/topics/1003.

Jing, L., 2006. A comparative analysis of the information communication technology industry in China. Chinese Econ. 39 (1), 74–83.

Jung, J., Lopez-Bazoc, E., 2020. On the regional impact of broadband on productivity: the case of Brazil. Telecommun. Policy 44 (1), 1–14.

Kiiski, S., Pohjola, M., 2002. Cross-country diffusion of the Internet. Inf. Econ. Policy 14, 297–310.

Killion, J. (April 20, 2020). Experts: Pandemic exposes NC's broadband Internet access disparities. Retrieved from https://pulse.ncpolicywatch.org/2020/04/22/experts-pandemic-exposes-ncs-broadband-internet-access-disparities/.

Koutroumpis, P., 2009. The economic impact of broadband on growth: a simultaneous approach. Telecommun. Policy 33, 471–485.

Kumar, R.R., Stauvermann, P.J., Samitas, A., 2016. The effects of ICT on output per worker: a study of the Chinese economy. Telecommun. Policy 40 (2–3), 102–115.

Lee, S., Lee, S., Chan-Olmsted, S., 2017. An empirical analysis of tablet PC diffusion. Telematics Inform. 34 (2), 518–527.

Lehr, W.H., Osorio, C.A., Gillett, S.E., & Sirbu, M.A. (2006). Measuring broadband's economic impact. Technical Report 99-07-13829. National Technical Assistance Training, Research, and Evaluation Project. Retrieved from https://www.itu.int/net/wsis/stocktaking/docs/activities/1288616475/MIT_Carnegie.pdf.

Li, J., Wu, S., 2020. Hulianwang, renkou guimo yu zhongguo jingji zengzhang: Laizi chenshi de shijiao. Contemp. Finance Econ. 1, 3–16.

Liebowitz, S. J., & Margolis, S. E. (2002). Network effects. In M. E. Cave, S. K. Majumdar, & I. Vogel- sang (Eds.), Handbook of Telecommunications Economics (Vol. 1, pp. 76–97). North Holland: Elsevier.

Lucas Jr., R.E., 1988. On the mechanics of economic development. J. Monetary Econ. 22, 3–42.

Mankiw, G.N., Romber, D., Weil, D.N., 1992. A contribution to the empirics of economic growth. Q. J. Econ. 107, 407–437.

Mayo, J.W., Wallsten, S., 2011. From network externalities to broadband growth externalities: a bridge not yet built. Rev. Ind. Organiz. 38, 171–190.

Nagarajan, S. (April 17, 2020). China's economy suffers its first contraction in 28 years, shrinking 6.8% in an 'extraordinary shock' to the global economy. Retrieved from https://www.businessinsider.com/china-economy-falls-first-quarter-2020-after-half-century-growth-2020-4.
National Bureau of Statistics. (n.d). Diqu shuju. Retrieved from http://data.stats.gov.cn/easyquery.htm?cn=E0101.
Organization for Economic Co-operation and Development (OECD), 2001. Understanding the Digital Divide. OECD Publications, Paris.
Reeves, R.V., Rothwell, J., 2020. Class and COVID: How the less affluent face double risks. Retrieved from https://www.brookings.edu/blog/up-front/2020/03/27/class-and-covid-how-the-less-affluent-face-double-risks/.
Shideler, D., Badasyan, N., Taylor, L., 2007. The economic impact of broadband deployment in Kentucky. Paper Presented at the Telecommunication Policy Research Conference.
Solow, R.M., 1956. A contribution to the theory of economic growth. Q. J. Econ. 70 (1), 65–94.
Song, Z., Wang, C., & Bergmann, L. (2020). China's prefectural digital divide: Spatial analysis and multivariate determinants of ICT diffusion. International Journal of Information Management, 52, 1-12. Retrieved from https://doi.org/10.1016/j.ijinfomgt.2020.102072.
Tencent (n.d.). Xinxing guanzhuang bingdu feiyan yiqing shishi zhuizong. Retrieved from https://news.qq.com/zt2020/page/feiyan.htm#/?nojump=1.
Thompson, H., & Garbacz, C. (2008). Broadband impacts on state GDP: Direct and indirect impacts. Paper presented at the International Telecommunications Society 17th Biennial Conference, Montreal, Canada.
Yamakawa, P., Rees, G.H., Salas, G.M., Alva, N., 2013. The diffusion of mobile telephones: an empirical analysis for Peru. Telecommun. Policy 37, 594–606.
Yang, F., Shanahan, J., 2003. Economic openness and media penetration. Commun. Res. 30 (5), 557–657.
Zhang, X., 2013. Income disparity and digital divide: the ICT consumption model and cross-country empirical research. Telecommun. Policy 37, 515–529.