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Research article

The impact of broadband speed on innovation: City-level evidence from China

Jialing Chen [a,b], Jiancheng Wang [c,*]

[a] Institute of Guangdong, Hong Kong and Macao Development Studies, Sun Yat-sen University, Guangzhou, China
[b] The Center for Studies of Hong Kong, Macao and Pearl River Delta, Sun Yat-sen University, Guangzhou, China
[c] International School of Business & Finance, Sun Yat-sen University, Zhuhai, China

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ABSTRACT

Previous studies have associated broadband with innovation, but most of them have focused on broadband access or broadband penetration rate rather than broadband speed. However, with the increase in the global broadband penetration rate, network speed is becoming a more important aspect of broadband development. Using a fixed effect model based on panel data from 274 cities in China from 2016 to 2018, we explore the impact of broadband speed on innovation and further validate the relationship by instrumental variable estimation and a series of robustness tests. The main findings are as follows: First, broadband speed significantly promotes patenting, and this effect is greater than the increase in broadband penetration rate. Second, the impact of broadband speed on promoting innovation is more substantial in cities with higher Internet penetration, GDP per capita, science and technology investment, and foreign direct investment. Third, broadband speed could promote innovation by facilitating patenting cooperation among firms. Fourth, we find no evidence of a diminishing marginal effect of broadband speed in this setting. This study has significant practical implications for emerging countries to encourage innovation by increasing broadband speed.

1. Introduction

As an essential digital infrastructure for emerging digital technologies such as big data, cloud computing, artificial intelligence, and blockchain, broadband networks have an increasingly noticeable impact on the economy [1]. Broadband networks and ICT technologies can play a critical enabling role in helping to achieve sustainable development goals by accelerating innovation, promoting education, increasing employment, and lifting people out of poverty [2]. The UN Broadband Commission for Sustainable Development strongly calls for governments worldwide to make deploying broadband network infrastructure a top priority. Countries worldwide are actively promoting broadband network infrastructure in practice as an essential element to promote industrial upgrading and accelerate the development of the digital economy. For example, China's "Broadband China" strategy proposed in 2013 regarded the broadband network as an important public infrastructure for China's economic and social development in the new era. It offered to narrow the gap in the development level of broadband network infrastructure between China and developed countries, with increasing broadband penetration and broadband speed as important elements. The Chinese government has made considerable efforts toward this goal, and the Internet penetration rate has risen from 45.8% in 2013 to 73% in 2021.

* Corresponding author.
E-mail address: wangjch67@mail.sysu.edu.cn (J. Wang).

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Researchers have long focused on how broadband Internet can contribute to economic and social development. Broadband Internet, as a general purpose technology, facilitates improvement of the quality of education and health services and improves the connection between government and society [3]. In the economic field, broadband networks fundamentally change how economic activity is organized [4]. Theoretically, broadband networks can reduce the five economic costs associated with digital economic activities: search, replication, transportation, tracking, and verification [5]. Broadband networks may accelerate information exchange and processing [6], reduce information asymmetries in labor markets [7], promote product innovation, entrepreneurial activity, job matching, and market competition [8], increase firm productivity [9,10], and promote economic growth [11]. Researchers have further focused on the impact of broadband on innovation [12,13] and mainly proposed two impact mechanisms, that is, broadband reduces the cost of information [5,14,15] and facilitates cooperation [16–18].

Several studies have examined the impact of broadband penetration on important economic variables such as economic growth, employment, and innovation. For instance, some studies have found that broadband adoption can increase employment [19,20], reduce unemployment in rural areas [21], increase business productivity [9], and promote economic growth [6]. However, others have revealed a limited effect of broadband on these economic variables [22,23]. Specifically, several researchers have focused on the effect of broadband on innovation [6,12–14]. Although characteristics such as housing prices [24], high-speed rail [25], and foreign direct investment (FDI) [26] are important factors influencing innovation, broadband also has a substantial impact on innovation. For example, [27] found a significant positive effect of broadband Internet on firms' innovation activities. In addition, [14] found that access to the Internet with a network speed of at least 10 Mbps can significantly facilitate regional innovation by reducing information costs.

As an increasing number of countries have made considerable progress in broadband penetration, broadband speed is becoming an important goal for broadband infrastructure development and is beginning to gain the attention of researchers [6]. Regarding the impact of broadband speed, numerous studies have found that broadband speed improvements can increase GDP [28], boost firm business in rural areas [29], and reduce unemployment [30]. However, to the best of our knowledge, except for [14], research exploring the impact of broadband speed on innovation is scarce. [14] examined the impact of the proportion of the population with access to each of the four threshold Internet speeds (10, 25, 50, and 100 Mbps) on regional innovation using county-level data for the United States. Their results found that access to higher Internet speeds does not necessarily increase the number of regional patents. Nevertheless, the impact of broadband speed on innovation requires more direct evidence.

To this end, this paper explores the impact of broadband speed on innovation using data from 274 cities in China from 2016 to 2018. China provides a suitable setting for this study as its government implemented strategies for improving broadband network infrastructure and network speed through the "Broadband China" strategy in 2013. As the central government of China has a strong policy implementation capability [31], the increase in broadband speed in Chinese cities, which the central government has mainly driven, has relatively strong externalities. The main contributions of our research are as follows: First, this paper utilizes the raw data of broadband speed to explore its impact on innovation instead of treating speed as a dummy or categorical variable. We suggest that raw data on network speed can better capture speed variations and help test whether network speed's effect on innovation is nonlinear. Second, compared with the existing studies that are mainly based on evidence from developed countries, we conduct a study on the impact of broadband speed on innovation and its mechanism based on evidence from China. Our study can complement existing research by providing empirical results from emerging countries.

The remainder of this paper is organized as follows. Section 2 presents the literature review and research hypothesis, Section 3 describes the data and research design, and Section 4 presents our empirical results. Finally, Section 5 is the conclusion and discussion.

2. Literature review and research hypothesis

2.1. Literature review

2.1.1. Broadband and economic outcomes

Studies on the relationship between broadband availability or adoption and economic outcomes are abundant and controversial.

On the one hand, numerous studies confirm that broadband access may promote economic development and employment. Several studies, based on different samples of OECD countries over time, have found that broadband infrastructure promotes economic growth [8,32]. At the enterprise level, a study on a large-scale micro survey in New Zealand found that adopting broadband increased an enterprise's productivity by 7–10% [9].

On the other hand, an equal amount of evidence suggests that this impact may be uneven, limited, or even insignificant. For example, a multi-country study found that although ICT promotes economic growth in all countries, poorer countries tend to gain more [11]. Furthermore, mobile ICT is essential for improving national productivity in developing countries. In contrast, wired ICT does not significantly impact developed or developing countries [33]. In addition, a study based on United States county-level data found that broadband expansion is associated with employment growth while not affecting average wages or employment rates [23].

Similarly, some studies have found that broadband has a mixed impact on employment. Studies in the United States found that communities [20] or counties [19] with broadband experience faster employment. However, other studies have found that these effects may be limited. For example, [34] found that employment in manufacturing and services is positively correlated with broadband penetration. [35] suggested that investment in broadband led to employment growth only in economically developed areas of the United States with ICT-skilled, high-income populations. Moreover, [23] showed that county-level broadband expansion does not increase wages or improve employment opportunities in the United States. Again, applying county-level data from the United States, [21] used both broadband availability and adoption data to empirically measure the contribution of broadband to economic growth in rural areas in the United States from 2001 to 2010. The results show that high-level broadband adoption in rural areas positively impacts income and employment growth but that broadband availability in rural areas is unrelated to job creation.

Some studies have attempted to address the endogeneity of broadband infrastructure improvements. For example, [10] explored the impact of broadband access on employment in Africa using DID estimation methods. They used progressive access to the submarine Internet cable as a policy shock in 12 African countries and revealed a significant positive effect. In addition, they used firm-level data to show that fast Internet creates more net employment by boosting firm entry, productivity, and exports. [36] exploited a unique public program of a staggered broadband infrastructure upgrade across rural municipalities in Italy as a quasi-natural experiment. They found that extended Asymmetric Digital Subscriber Line (ADSL2+) availability increased firm revenues and total factor productivity but did not affect personnel costs or employment. In contrast, [22] conducted several instrumental variable regressions and found that DSL network availability did not reduce unemployment rates.

2.1.2. Broadband speed and its economic outcomes

Broadband speed has become increasingly essential for improving business productivity and quality of life. Numerous countries have developed national broadband plans to improve broadband speed. However, few relevant studies on the topic [37] provide inconclusive evidence [33]. The literature in this field mainly focuses on the impact of broadband speed on GDP, business, and employment.

Both positive and limited effects of broadband speed on economic growth have been found in the established literature. [28] used a two-stage fixed effects panel model to study the quarterly balanced panel datasets of 34 OECD countries from 2008 to 2010. They found that, compared to 2008, the doubling of broadband speed (from 8.3 Mbps to 16.6 Mbps) contributed 0.3% to GDP growth. [29] modeled broadband speed as a binary dummy variable, indicating whether there is at least one high-speed provider (one who provides a download speed of at least 3 Mbps and an upload speed of at least 768 Kbps) in a census area. The results show that broadband speed positively impacts corporate business in rural areas for some industries with several exceptions (such as health care or public administration). [6] included the quadratic term of broadband speed to test the nonlinear relationship between broadband speed and economic growth in the 35 OECD countries between 2002 and 2016. The coefficient of the quadratic term is negative and significant, indicating that broadband speed has diminishing returns on GDP. [33] collected wired and mobile Internet speeds in various countries from a quarterly report released by Akamai to study the impact of network speed on national productivity. They found that mobile broadband network speed is essential for improving productivity in developing countries.

The findings regarding the impact of broadband speed on employment are mixed. [30] defined a network speed below 100 Mbps as low, between 100 and 1000 Mbps as high, and above 1000 Mbps as ultra-high and investigated the impact of broadband speed on the county-level unemployment rate in Tennessee. The results revealed that the unemployment rate in counties with high Internet speed was approximately 0.26% lower than in counties with low Internet speed. There is no significant difference between the impact of high-speed and ultra-high-speed broadband. [38] classified the Internet availability data into four categories: Superfast (1 GB/s or faster), Fast (100 MB/s to 1 GB/s), Normal (3 MB/s to 100 MB/s), and NO (no broadband or Internet access). The analysis showed that the impacts of Superfast and Fast broadband on the county employment rate are not significantly different from the benefits generated by Normal broadband. In addition, [39] quantified the effect of higher broadband speeds (10 Mbps versus 25 Mbps) on economic variables, including employment, personal income, and labor income in the United States, and the results revealed no economic payoff from the 15 Mbps speed increment from 2013 to 2015. According to [39], the positive benefits of broadband reported by [34] may be false results caused by selection bias. Moreover, [40] identified an econometric error in the study by [38], suggesting that researchers must improve the existing model to reveal the relationship between broadband speed and employment.

2.2. Research hypothesis

Internet access is an essential determinant of innovation [13], but it has received little attention in the literature [14]. Some studies found that broadband can promote innovation, but this effect may be limited. [12] analyzed ICT innovation in 40 countries from 1999 to 2013 and found that high-level broadband infrastructure is related to high-level ICT innovation. [27] demonstrated that broadband Internet significantly and positively impacts enterprise innovation activities in Germany. [14] argued that the accessibility of the Internet, rather than Internet speed, facilitates innovation. They emphasized the indirect role of Internet accessibility in lowering information costs and therefore boosting regional innovation activity, building on theoretical and empirical evidence. [41] found that broadband Internet access mainly promotes invention patents rather than design patents. Furthermore, [13] found that broadband positively affects rural enterprises' innovation capabilities.

Previous studies have provided evidence about two main mechanisms regarding the theoretical mechanisms linking broadband and innovation. First, broadband favors innovation by lowering information costs. [14] constructed a theoretical model to illustrate the positive impact of reduced discovery costs on innovation and empirically tested this inference using county-level data from the United States. They found that Internet access is a mechanism for lowering discovery or information costs, which can increase patent filings. Specifically, they showed that if agents can learn at a low cost whether the innovation has been patented, how many others are competing in the patent race, and who is and will be pursuing such protection, they are more likely to pursue the project. Thus, Internet access can indirectly increase the number of patent filings. Firms with a good broadband connection can efficiently obtain knowledge and information that is relevant and valuable for firm innovation decision-making [15].

Second, broadband enhances innovation by easing collaborations. [16] found that a decrease in collaboration costs resulting from adopting Bitnet (an early version of the Internet) did seem to facilitate a general increase in multi-institutional collaboration. Specifically, they suggested that the most salient effect of Bitnet may have been to facilitate gains from trade through the increased use of underutilized research equipment or the heightened specialization of research tasks. Similarly, [17] found that the availability of Bitnet on a scientist's campus not only provided greater access to materials and equipment but also allowed researchers to share ideas at a lower rate and across greater distances, which had a positive effect on their productivity and collaborative network. [18] demonstrated robust empirical evidence that the adoption of basic Internet significantly reduced the coordination costs of research teams and was associated with an increased likelihood of collaborative patents from geographically dispersed teams.

Overall, there is a relative wealth of research on broadband access and innovation, but few studies have focused on speed and innovation. The existing studies mainly present the following characteristics. First, empirical studies related to the economic impact of broadband access or speed have found positive [8,9,19,20], limited, or even insignificant impacts [23,39]. The economic impact of broadband speed requires further examination. Second, existing studies have usually treated broadband speed as whether the speed reached a specific threshold. For example, [14] divided Internet speed into four thresholds of 10 Mbps, 25 Mbps, 50 Mbps, and 100 Mbps, whereas [39] divided it into two thresholds of 10 Mbps and 25 Mbps. The selection of a certain threshold may provide some practical implications. For example, the threshold of 100 Mbps can help investigate whether fiber brings significant benefits. However, this treatment of network speed is somewhat dependent on the choice of threshold and is not conducive to empirically identifying potential nonlinear relationships between variables. Third, the current research on broadband access or speed affecting innovation is largely based on evidence from developed countries. For example, the only empirical study, to our knowledge, available on the impact of broadband speed on innovation conducted by [14] was based on evidence from the United States. However, according to the Q4 2015 State of the Internet Report published by Akamai, the average Internet speed in the United States is 14.2 Mbps, whereas the average Internet speed in China is 4.1 Mbps. Can findings based on samples from developed countries be applied to emerging countries with relatively low Internet speeds? This question remains to be explored.

Based on the above analysis, we propose the following hypothesis.

Hypothesis 1. Broadband speed has a positive effect on urban innovation.

3. Methods

3.1. Data, variables, and analyses

3.1.1. Instrumental variables

Following [42], who used the cable distance to the local telephone exchange as the instrumental variable for ADSL broadband speed, we construct our instrumental variables for broadband speed as the city's shortest distance to the node city of the trunk line in 2000 multiplied by the year dummies. At the beginning of China's reform and opening up, its communication infrastructure lagged far behind the world average. China had only six communication mainlines per 1000 people compared to 508.8 in the United States, 438.3 in Japan, and 139.9 in Russia [43]. Since 1986, China has built a communication network mainly based on optical fiber transmission. From 1986 to 1990, China built an optical fiber trunk network from Nanjing to Wuhan to introduce and absorb foreign optical fiber

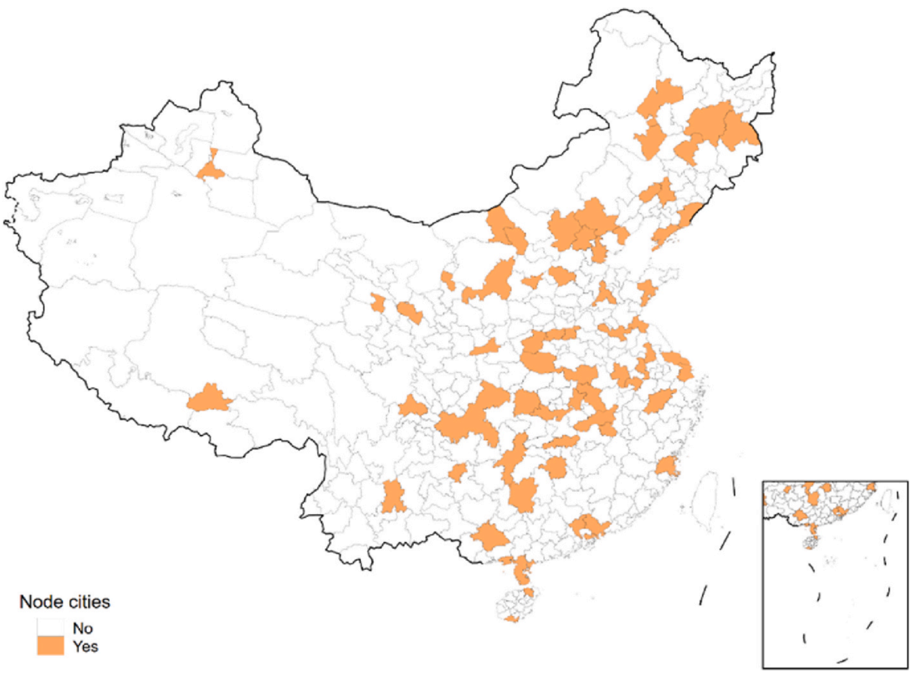

Fig. 1. Sixty-four node cities of China's optical cable network trunk in 2000.

communication technologies. From 1991 to 1995, China laid 23 optical cables with a total length of 37,000 km, solving the problem of long-distance communication between critical cities. From 1996 to 1998, China laid 25 optical cables with a total length of 34,000 km and built “eight vertical and eight horizontal” optical fiber cable trunk networks. The trunk line from north to south is “vertical,” and from east to west, it is “horizontal.” They crisscross and form a primary trunk transmission network that extends in all directions. Short-distance optical fiber cables were later built as extensions of existing networks, making the entire network more flexible and ideal. By the end of 2000, the length of optical cable lines was approximately 1.25 million km, including 290,000 km of long-distance trunk optical cables. The backbone network completely revived China’s long-distance communication situation and laid a solid foundation for its communication modernization.

As the backbone network is the foundation of China’s current communication system, it has affected the network speed of the cities in our sample. Cities close to the trunk are more likely to be connected to the network; thus, the distance to the trunk node city is negatively correlated with network speed, which meets the relevance assumption of instrumental variables. The exclusion restrictions for the validity of our instrument require that a city’s shortest distance to network node cities cannot affect urban innovation directly or through indirect channels other than broadband speed. Our three main justifications are as follows: First, China’s state-level departments have formulated plans to construct an optical fiber cable backbone network. Cities cannot affect the formulation of specific routes or the selection of node cities in this plan. Second, since China built this network trunk line around 2000, the city’s current innovations will not affect the location of the network trunk node cities two decades before. Third, one may be concerned that the shortest distance to the nearest network trunk node is correlated with the distance to megacities. Usually, megacities have greater market effects or agglomeration economies. Consequently, the distance to megacities is potentially correlated with innovation. Therefore, we delete the samples of node cities and control for the city’s shortest distance to megacities for robustness. Since distance is time-invariant and is absorbed by city-fixed effects, we multiply it by time and utilize these interaction terms as instrumental variables for broadband speed. The node city information used to calculate a city’s shortest distance to the backbone network is collected from China’s trunk optical cable transmission network at the end of 2000, as published by China’s Ministry of Information Industry (Fig. 1).

3.1.2. *“Broadband China” pilot cities*

To alleviate the problems of slow Internet speed and low coverage, the Chinese government released the “Broadband China” strategy in August 2013. The strategy put forward clear construction goals, tasks, and policy measures to guide and promote the construction of broadband infrastructure in China. To implement this strategy, the Chinese government selected 119 cities as “Broadband China” pilot cities in 2014, 2015, and 2016. The selected cities would increase public financial support for broadband development and vigorously enhance high-speed broadband access, thus driving up the average Internet speed of the pilot cities.

Since the pilot cities selected for the Broadband China strategy and their pilot timing were determined by the Chinese central government, individual cities are unlikely to have influenced this decision. Moreover, this policy would improve broadband infrastructure and increase Internet speed in pilot cities. Therefore, in the robustness check, we change the measure of broadband speed. Instead of using a continuous variable to measure broadband speed, we use a dummy variable that takes the value of one when a city is selected as a “Broadband China” pilot city and zero otherwise. Since we use a sample at the city level in the benchmark regression, we

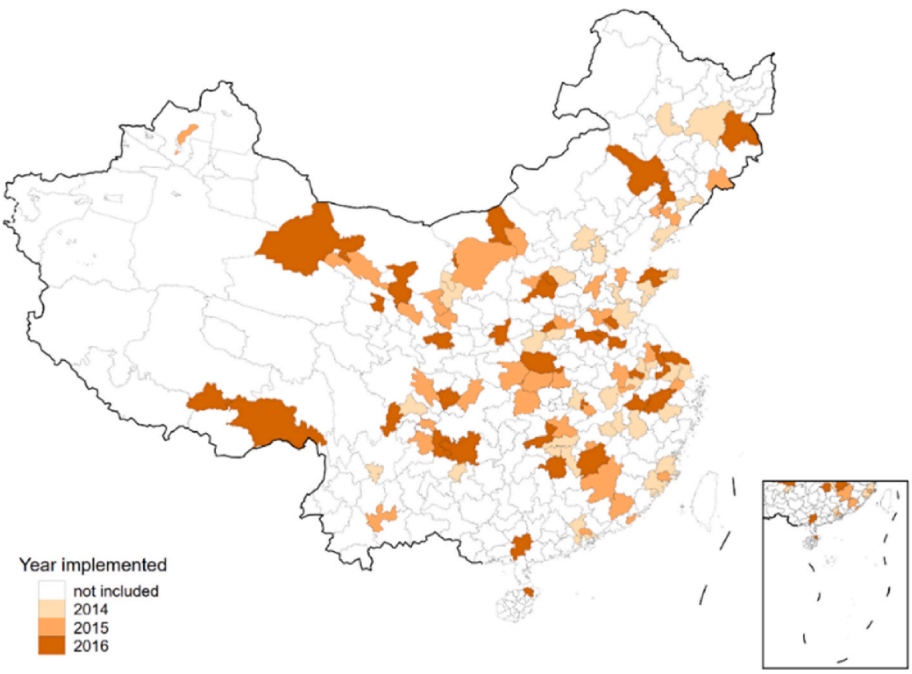

Fig. 2. “Broadband China” pilot cities in 2014, 2015, and 2016.

remove the county-level cities, the district, and the autonomous prefecture from the pilot cities. We retain only 109 pilot cities (Fig. 2).

3.1.3. Sample selection and data source

Our study uses the following three main samples, in which we winsorize all the continuous variables at the 1% and 99% levels to exclude the influence of outliers:

First, we utilize panel data for 274 cities in China from 2016 to 2018. Referring to [12], who used the number of ICT patents granted per 1 million inhabitants to measure ICT innovation, we take the number of patent applications per 10,000 people as a proxy variable for innovation. We collect city-level patent data from the China Research Data Service database (www.cnrds.com), including the total number of patent applications; the total number of patents granted; and the number of invention, utility model, and design patent applications. We employ the natural logarithm of the one-period-lag broadband speed as the independent variable. Speedtest is a large network speed measurement company (www.speedtest.cn) that has partnerships with major Chinese telecom operators. We obtain city-level broadband speed data from Speedtest for 2015–2017. In addition, we collect a set of variables from the CEIC database (www.ceicdata.com) to control for urban heterogeneity. Following [41], we include the natural logarithm of GDP per capita, the natural logarithm of FDI, the natural logarithm of the number of higher education institutions, the ratio of secondary industry output to GDP, and the Internet penetration rate. In addition, we control for the share of fiscal expenditures on science and technology. Local government spending is also a potential factor influencing innovation, as it can indicate whether the region has good access to utilities, transportation, education, and other public services. Considering the impact of high-speed rail [25] and housing prices [24] on innovation, we also control for the opening of high-speed rail and the price of commercial housing.

Second, in the robustness analysis section, we use panel data for 280 cities in China from 2011 to 2018. We construct a dummy variable instead of a continuous variable for broadband speed, which takes the value of one when a city has been selected as the pilot city of the "Broadband China" policy and zero otherwise. Since there is a time lag between network speed and innovation, we employ the number of patent applications per 10,000 people one period ahead (2012–2019) and two periods ahead (2013–2020) as dependent variables for innovation. In addition, we control for the same city characteristic variables as the first sample.

Third, in the mechanism analysis, we merge the data of 2362 listed companies in China with city-level data on broadband speed and city characteristics from 2015 to 2017. Specifically, we measure interfirm patent cooperation using joint patent applications and granted patents of listed companies. We use data from one-period-ahead (2016–2018) and two-period-ahead (2017–2019) joint patents. In addition, we control for the characteristics of these firms for 2015–2017, including firm age, employee structure, and financial indicators. We also process the sample of enterprises according to the following criteria: (1) only retain the sample whose firm type is the listed company itself; (2) delete the listed companies whose industries are finance and insurance; (3) only retain the sample whose listing status is normally listed.

3.2. Model specification

Considering a time lag between broadband speed and innovations, we employ a 1-year lagged fixed effects model to test Hypothesis 1 as follows:

$$Innovation_{i,t} = \alpha_0 + \beta_1 log\ (CSpeed_{i,t-1}) + \beta_2 X_{i,t-1} + \delta_i + \gamma_t + \varepsilon_{i,t,} \tag{1}$$

where $\boldsymbol{Innovation_{i,t}}$ is the number of patent applications per 10,000 people in city $\boldsymbol{i}$ in year. $\boldsymbol{CSpeed_{i,t-1}}$ is the broadband speed of city $\boldsymbol{i}$ in year *t-1*. $X_{i,t-1}$ are the city covariates, including the natural logarithm of GDP per capita, the natural logarithm of FDI, the natural logarithm of the number of higher education institutions, the ratio of secondary industry output to GDP, the share of fiscal spending on science and technology, the Internet penetration rate, the opening of high-speed rail, and the price of commodity housing. δ_i represents the time-invariant city-fixed effects; γ_t, the year-fixed effects; and $\varepsilon_{i,t}$, the error term.

Eq. (1) estimates will be biased if an endogeneity problem exists. Some unobservable missing variables, such as the preferences of inventors, which are vital for innovation and usually require a high-speed network, may exist. We use a fixed effects panel model to alleviate this concern. In addition, reverse causality can also lead to biased estimates. For example, broadband service providers may prefer to invest in more innovative cities. Thus, there is a concern that a city's innovation may affect its network speed. In this study, we argue that reverse causality may be relatively weak for the following two reasons. First, our dependent variable is one-period-ahead patent applications, which helps to attenuate the inverse effect of innovation on broadband speed. Second, the city-level changes in broadband speed used in this paper are mainly driven by the Chinese central government and are relatively exogenous. To identify causality, we employ an instrumental variable approach.

The 2SLS models are as follows:

$$log\ (CSpeed_{i,t-1}) = \gamma_0 + \gamma_1\ IV_{i,t-1} + \gamma_2 X_{i,t-1} + \varepsilon_i + \mu_{t-1} + \theta_{i,t-1}\ , \tag{2}$$

$$Innovation_{i,t} = \delta_0 + \delta_1\ log\ \left(\widehat{CSpeed}_{i,t-1}\right) + \delta_2 X_{i,t-1} + \sigma_i + \varphi_t + \omega_{i,t}\ , \tag{3}$$

where Eq. (2) is the first-stage model and Eq. (3) is the second-stage model. In Eq. (2), $IV_{i,t-1}$ are the instrumental variables for the broadband speed of city $\boldsymbol{i}$ in year *t-1*. The control variables are the same as those in Eq. (1). ε_i represents the time-invariant city-fixed effects, and μ_{t-1} represents the year-fixed effects. $\theta_{i,t-1}$ is the error term. In Eq. (3), $\boldsymbol{Innovation_{i,t}}$ is the number of patent applications per 10,000 people for city $\boldsymbol{i}$ in year $\boldsymbol{t}$. We use the predicted broadband speed in Eq. (2) as the independent variable and control for the city characteristics in Eq. (1). σ_i represents the city-fixed effects and φ_t the year-fixed effects. $\omega_{i,t}$ is the error term.

4. Empirical results

4.1. Summary statistics

Table 1 presents the descriptive statistics for the variables in the main results. The mean value of innovation performance (number of patent applications per 10,000 people) is 1.76, with a standard deviation of 2.32 and a maximum value of 16.78, indicating that the number of patent applications per 10,000 people in Chinese cities is low and varies widely between cities. The mean value of broadband speed is 9.01, and the maximum value is 30.39, indicating that the broadband speed in Chinese cities is relatively low. Fig. 3 shows the city-level broadband speed in 2017.

4.2. Baseline results

Table 2 presents the estimation results of Eq. (1). Columns (1) and (2) present the regression results of broadband speed on innovation performance. Considering the possible existence of temporal trends and the time-invariant factor that can affect innovation, we control the year- and city-level fixed effects. Column (1) suggests that broadband speed significantly and positively affects urban innovation performance. Nevertheless, the result could be biased by some heterogeneity characteristics that can affect urban innovation such as economic development, FDI, housing prices, and the number of higher education institutions. Therefore, we further control these characteristics in column (2), and the coefficient is still positive and significant, indicating that cities have higher innovation performance when they have faster broadband speed. Specifically, the coefficient of log*(Broadband speed)* suggests that a 10% rise in broadband speed will increase the number of patent applications per 10,000 people in the city by 0.06. The above results support Hypothesis 1. In addition, we run Eq. (1) on the standardized variables and find that the coefficient on the natural logarithm of broadband speed is larger than that on the Internet penetration rate at the 10% significance level.[1]

4.3. Instrumental variable regression

The above results may be affected by endogeneity. To assess causality in the positive relationship between broadband speed and innovation growth, we instrument for broadband speed using the shortest distance from the city to the node city of the "eight vertical and eight horizontal" backbone networks built in 2000, multiplied by the year dummies. Table 3 presents the estimation results of the 2SLS regressions. We examine the effect of the two instrumental variables on broadband speed in column (1). The results indicate that the two instrumental variables have a significantly negative effect on a city's broadband speed. In column (2), we include the residual of the first-stage regression in column (1) and run Eq. (1). The coefficient of the residual is significant at the 1% level, indicating that our model does suffer from endogeneity problems. Column (3) presents the results of the second-stage regression. We apply the predicted values for broadband speed as the independent variable and run Eq. (3). The p-value of the Hansen J statistic is 0.13, indicating that instrumental variables are exogenous. The effect of broadband speed is positive and significant at the 5% level.

Most node cities are provincial capitals and tend to have larger markets and better broadband network development. Some may worry that the shortest distance to the nearest network trunk node is correlated with distance to major cities (and thus, to market effects, agglomeration economies, etc.), which is potentially correlated with innovation. To alleviate this concern, we follow [44] and exclude the node cities as well as control for the shortest distance to megacities[2] and repeat the 2SLS regression (columns (4) and (6)). The effect of broadband speed in column (6) is slightly smaller than that in column (3); however, it is still significant and positive. Overall, the baseline results are still robust, thus verifying Hypothesis 1. Compared to the magnitude of the speed effect in column (2) of Table 2, the effect in column (6) of Table 3 increases by approximately 290%. We suggest two possible reasons: First, the reverse causality in this paper is relatively weak. Our dependent variable is one-period-ahead patent applications, which helps attenuate innovation's inverse effect on broadband speed. In contrast, the city-level changes in broadband speed used in this paper are primarily driven by the Chinese central government and are relatively exogenous. Second, our endogeneity problem is mainly caused by omitted variables that vary over time. To reduce the bias from omitted variables, we add control variables such as house price, the opening of high-speed rail, and road density to the 2SLS regressions. Nevertheless, there are other omitted variables that we cannot control. Thus, OLS estimation, in this case, may result in a downward bias in the coefficient estimates of the broadband speed.

4.4. Robustness check

In this study, we conduct a series of robustness tests to ensure the reliability of our conclusions, as reported in Tables 4 and 5.

[1] After standardization, the coefficient of the natural logarithm of broadband speed is 1.27*** and the coefficient of Internet penetration is 0.47*.

[2] According to China's seventh census, there are 21 megacities (urban areas with a resident population of 5 million or more) in China, including Shanghai, Beijing, Shenzhen, Chongqing, Guangzhou, Chengdu, Tianjin, Shanghai, Wuhan, Dongguan, Xi'an, Hangzhou, Foshan, Nanjing, Shenyang, Qingdao, Jinan, Changsha, Harbin, Zhengzhou, Kunming, and Dalian.

Table 1
Descriptive statistics.

	Observations	Mean	Standard deviation	Min	Max
Dependent variables					
Total patent applications per 10,000 people, 2016–2018	822	1.76	2.32	0.04	16.78
Total patent applications per 10,000 people, 2017–2019	822	2.02	2.74	0.07	19.15
Total patents granted per 10,000 people, 2017–2019	822	1.23	1.70	0.04	13.26
Invention patent applications per 10,000 people, 2016–2018	822	0.67	0.10	0.01	7.55
Utility model patent applications per 10,000 people, 2016–2018	822	0.81	1.02	0.02	7.82
Design patent applications per 10,000 people, 2016–2018	822	0.28	0.50	0.01	5.54
Independent variable					
City's broadband speed, 2015–2017	822	9.01	4.29	3.79	30.39
Instrumental variable					
Shortest distance to the node cities (1000 KM)	822	0.10	0.09	0.00	0.45
City-level characteristics, 2015–2017					
log (GDP per capita)	822	10.75	0.52	9.24	11.83
The ratio of secondary industry output to GDP	822	44.83	9.21	14.39	84.09
Share of fiscal expenditures on science and technology	822	1.62	1.58	0.07	12.65
log (FDI)	822	5.30	2.07	−3.91	8.91
Internet penetration	822	21.77	10.49	4.57	88.93
Having at least one high-speed railway station	822	0.65	0.48	0.00	1.00
Commodity house price	822	5.39	3.34	2.25	45.15
log (Number of higher education institutions in the city)	822	1.45	1.11	0.00	4.19
Road density	822	1.12	0.50	0.08	2.63
Shortest distance to the megacities (1000 KM)	822	0.24	0.25	0.00	2.35

Notes: SD, standard deviation; FDI, foreign direct investment; GDP, gross domestic product.

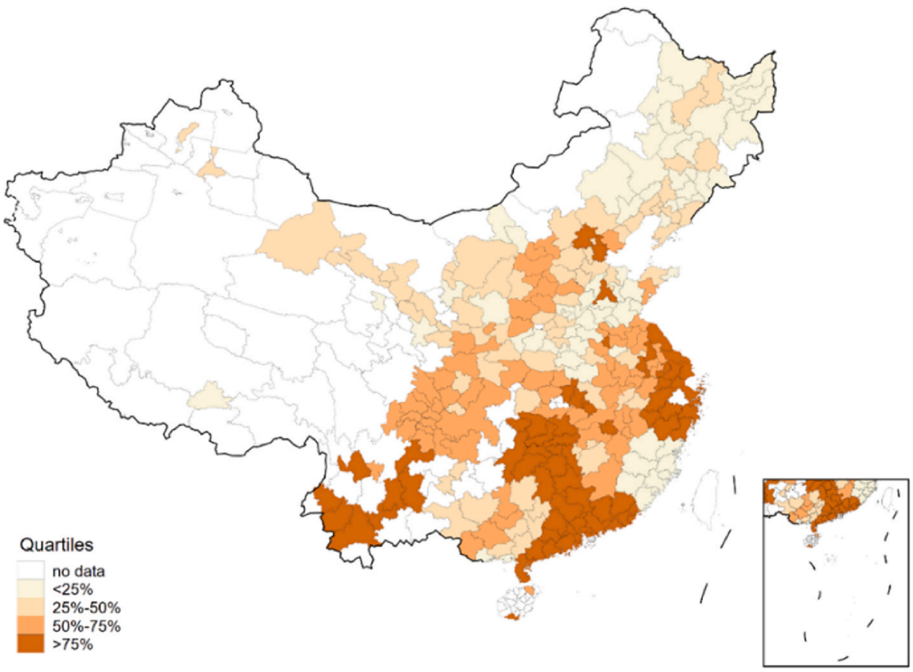

Fig. 3. City-level broadband download speed in 2017.

4.4.1. Replacing the dependent variable and controlling for province-year effects

Broadband speed may be affected by time-varying factors at the provincial level, such as telecommunications development policies formulated by provincial governments. Therefore, we extend the baseline regressions with the interaction terms of the province and year dummies in columns (1) and (2). The coefficients of broadband speed verify the robustness of the baseline results. In addition, we replace the dependent variable with the total number of patent applications two periods ahead in column (3). The time lag between filing and granting a patent is usually no less than one year. Therefore, broadband speed is generally unlikely to affect the number of patents granted one period ahead. We replace the dependent variable with the total number of patents granted two periods ahead in column (4). The effects of broadband speed on innovation in columns (3) and (4) remain significant and positive, further verifying the robustness of the baseline regression results. The results show that a 10% increase in broadband speed can increase the number of

Table 2
Broadband speed and patent applications.

	(1)	(2)
	Total patent applications	
log(*Broadband speed)*	0.77*** (0.23)	0.61*** (0.21)
log(*GDP* per capita*)*		0.09 (0.33)
Ratio of secondary industry output to GDP		0.01 (0.01)
Share of fiscal expenditures on science and technology		0.27*** (0.08)
log(*FDI)*		−0.00 (0.02)
Internet penetration		0.02* (0.01)
Having high-speed rail		0.19 (0.13)
Commodity house price		0.10 (0.09)
log(*Number of higher education institutions in the city)*		0.47* (0.24)
Constant	0.02 (0.45)	−2.98 (2.99)
Year FE	Yes	Yes
City FE	Yes	Yes
Observations	822	822
R-squared	0.23	0.34

Notes: Standard errors clustered at the city level are shown in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% confidence levels, respectively. FDI, foreign direct investment; GDP, gross domestic product; FE, fixed effects.

Table 3
Instrumental variable regression.

	(1)	(2)	(3)	(4)	(5)	(6)
	log (Broadband speed)	Total patent applications	Total patent applications	log (Broadband speed)	Total patent applications	Total patent applications
predicted log(*Broadband speed)*			2.73** (1.16)			2.37** (1.12)
log(*Broadband speed)*		2.73*** (0.81)			3.11*** (1.17)	
residual of regression in the first stage		−2.19*** (0.81)			−2.37** (1.12)	
*Shortest distance to node cities*year2016*	−0.47*** (0.17)			−0.53** (0.21)		
*Shortest distance to node cities*year2017*	−0.44*** (0.17)			−0.47** (0.23)		
Shortest distance to megacities year 2016*				0.01 (0.11)		−0.23 (0.19)
Shortest distance to megacities year 2017*				−0.03 (0.12)		−0.29 (0.22)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	822	822	822	630	630	630
*F test of that coefficients on Distance*year 2016 and Distance*year 2017 are jointly equal to 0*	119.90			31.15		
p-value	0.00			0.00		
Hansen J statistic			2.27			0.16
p-value of Hansen J statistic			0.13			0.69
R-squared	0.77	0.34	0.07	0.81	0.40	0.27

Notes: Standard errors clustered at the city level are shown in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% confidence levels, respectively. FE, fixed effects.

patent applications per 10,000 people two periods ahead and patents granted per 10,000 people two periods ahead by 0.05 and 0.05, respectively.

4.4.2. Replacing the independent variable

In addition to the above tests, we change the measure of broadband speed. Instead of using a continuous variable to measure broadband speed, we use a dummy variable *Broadbandcity* that takes the value of one when a city has been selected as a "Broadband China" pilot city and zero otherwise. We rerun Eq. (1), and the results are presented in Table 5 (see Appendix A Table A1 for detailed descriptive statistical information). *Broadbandcity* is positive and statistically significant at the 1% level in both regressions. The results show that the implementation of the "Broadband China" pilot policy increased the number of patent applications per 10,000 people by 0.30 and 0.30 in the first and second years after implementation, respectively, which further supports Hypothesis 1.

4.5. Heterogeneity analysis

We explore whether the positive relationship between broadband speed and innovation exhibits heterogeneity (Table 6). We add the interaction terms of the four variables and broadband speed into the benchmark regression. In column (1), we add the interaction term of Internet penetration and broadband speed. The higher the Internet penetration, the wider the user group affected by the

Table 4
Robustness analysis.

	(1)	(2)	(3)	(4)
	Total patent applications	Total patent applications	Total patent applications	Total patents granted
log*(Broadband speed)*	0.78*** (0.24)	0.60*** (0.22)	0.47*** (0.18)	0.49*** (0.12)
*Province*year2016*	Yes	Yes		
*Province*year2017*	Yes	Yes		
Controls	No	Yes	Yes	Yes
Constant	0.00 (0.46)	−2.95 (3.15)	5.92* (3.10)	−0.64 (1.53)
Year FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Observations	822	822	822	822
R-squared	0.23	0.34	0.27	0.55

Notes: The dependent variables in columns (3) and (4) are the number of patent applications per 10,000 people two periods ahead and the number of patents granted per 10,000 people two periods ahead, respectively. Standard errors clustered at the city level are shown in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% confidence levels, respectively. FE, fixed effects.

Table 5
"Broadband China" pilot policy and patent applications.

	(1)	(2)
	Total patent applications one period ahead	Total patent applications two periods ahead
Broadbandcity	0.30*** (0.06)	0.30*** (0.07)
Controls	Yes	Yes
Constant	−1.20 (1.57)	−0.20 (1.85)
Year FE	Yes	Yes
City FE	Yes	Yes
Observations	2240	2240
R-squared	0.92	0.90

Notes*:* The sample used in the above regression is a panel of 280 cities from 2011 to 2018. Standard errors clustered at the city level are shown in parentheses.[31] ***, **, and * indicate significance at the 1%, 5%, and 10% confidence levels, respectively. FE, fixed effects.

Table 6
Heterogeneous impact of broadband speed on patent applications.

	(1)	(2)	(3)	(4)
	Total patent applications			
log*(broadband speed)*	0.43** (0.21)	0.33* (0.19)	0.28 (0.19)	0.39** (0.19)
log*(broadband speed)*Internet penetration*	0.04*** (0.01)			
log*(broadband speed)**Log*(GDP* per capita*)*		0.80*** (0.21)		
log*(broadband speed)*Share of fiscal expenditure on science and technology*			0.37*** (0.07)	
log*(broadband speed)**log*(FDI)*				0.14*** (0.04)
Controls	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Constant	0.30 (0.80)	0.62 (0.78)	0.94 (0.69)	0.29 (0.82)
Observations	822	822	822	822
R-squared	0.39	0.38	0.43	0.36

Notes*:* Standard errors clustered at the city level are shown in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% confidence levels, respectively. We centralized all variables in the interaction terms. FDI, foreign direct investment; GDP, gross domestic product; FE, fixed effects.

increased broadband speed. In column (2), we include the interaction term of broadband speed and the natural logarithm of per capita GDP, which measures regional economic development. A high level of economic development implies high Internet penetration and strong technological innovation ability. Column (3) includes the interaction term of broadband speed and R&D input, measured by the share of fiscal expenditure on science and technology. The higher the share, the more importance the government attaches to innovation and the better the innovation environment. In column (4), we include the interaction term of broadband speed and the natural logarithm of FDI, reflecting the openness of cities. The more open a region is, the more likely it is to be exposed to new ideas, technologies, and innovation output and thus more likely to innovate. All interaction coefficients are positive, which indicates that cities with higher Internet penetration, level of economic development, R&D input, and FDI are more likely to innovate successfully.

Table 7 shows the impact of broadband speed on the number of applications for different types of patents. The estimations reveal a

Table 7
Broadband speed and applications for different types of patents.

	(1)	(2)	(3)	(4)	(5)	(6)
	Invention patents		Utility model patents		Design patents	
log*(Broadband speed)*	0.39*** (0.15)	0.31** (0.13)	0.39*** (0.10)	0.28*** (0.09)	−0.04 (0.05)	−0.01 (0.05)
Controls	No	Yes	No	Yes	No	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Constant	−0.17 (0.29)	−3.43* (2.03)	−0.11 (0.19)	−0.40 (1.42)	0.34*** (0.10)	0.60 (0.65)
Observations	822	822	822	822	822	822
R-squared	0.11	0.19	0.31	0.42	0.01	0.08

Notes: Standard errors clustered at the city level are shown in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% confidence levels, respectively. FE, fixed effects.

positive relationship between the city's patent applications and broadband speed, except for design patents.[4] To some extent, our findings are consistent with existing studies. For example, using county-level data from the United States, [14] found that broadband access promotes utility model patenting. Based on firm-level data from China, [41] found that broadband Internet access primarily promotes invention patents rather than design patents.

4.6. Mechanism analysis

According to the previous analysis, broadband speed may promote innovation through two main mechanisms by reducing information costs [14] and facilitating collaboration [16–18]. Owing to data limitations, this study only tests the mechanism of broadband speed for cooperation. Based on Eq. (1), we replace the dependent variable with the number of joint patent applications and grants of firms. We also control for firm-level characteristics, including employee education structure, total assets, return on assets, leverage, and the total number of employees. The detailed descriptive statistical information is shown in Appendix A Table A2.

Since the numbers of firm's joint patents applications and grants are count variables and have many zero values, OLS estimates may lead to inconsistencies. In addition, both the distributions of the firm's joint patents applications and grants show an overdispersion problem (For example, the mean of the firm's patents granted two periods ahead is 2.51, while the standard deviation is 9.78). Therefore, following the existing literature [45–51], we use the fixed effects negative binomial model. The results are shown in Table 8. The dependent variables in columns (1) and (2) are the numbers of firm's patents applications one period ahead and two periods ahead. The dependent variables in columns (3) and (4) are the numbers of firm's patents granted one period ahead and two periods ahead. The coefficients of log*(Broadband speed)* in columns (1) to (3) are positive but insignificant, while the coefficient for broadband speed in column (4) is 0.23 and significant at the 5% level. This finding partly validates that broadband speed may increase innovation by promoting cooperation.

4.7. The nonlinear effects of broadband speed

Some studies have suggested that the economic impact of broadband speed may not be linear. [6] added a quadratic term for broadband speed to the model and found that the squared term is significant and negative, indicating that the marginal return to GDP from broadband speed is decreasing. In contrast, [28] found the squared term to be significant and positive, indicating increasing marginal returns. Both studies focus on the effect of broadband speed on economic growth rather than innovation. Is there a nonlinearity in the effect of broadband speed on innovation? We test this question by adding the quadratic term of the natural logarithm of broadband speed to Eq. (1). Table 9 shows the estimation results. We add the quadratic term of broadband speed and control for year and city-fixed effects in column (1) and further control for city characteristics in column (2). The estimated coefficients of broadband speed in columns (1) and (2) are insignificant, whereas those of the quadratic terms are significantly positive at the 1% and 5% levels, respectively. Thus, our study does not find the diminishing returns of broadband speed found in [14].

5. Discussion and conclusions

Based on panel data of 274 cities in China from 2016 to 2018, our study finds a positive relationship between broadband speed and urban innovation. Specifically, a 10% increase in broadband speed can increase the number of patent applications per 10,000 people in cities by 0.06. Considering that the mean value of patent applications per 10,000 people in the sample was 1.76, the innovation payoff of broadband speed is substantial. Furthermore, we verify that increasing broadband speed promotes urban innovation using instrumental variable estimation and a series of robustness tests.

The heterogeneity analysis reveals that the impact of broadband speed on promoting innovation is more substantial in cities with

[3] The estimation code is as follows: reghdfe patents Broadbandcity controls, absorb(year city) vce(cluster city).

[4] The instrumental variable regression estimates also show a positive relationship between patent filings and broadband speed in cities, except for design patents.

Table 8
Mechanism analysis.

	(1)	(2)	(3)	(4)
Negative	firm's patents applications		firm's patents granted	
Binomial regression	one period ahead	two periods ahead	one period ahead	two periods ahead
log*(Broadband speed)*	0.10 (0.14)	0.14 (0.13)	0.02 (0.11)	0.23** (0.14)
Firm controls	Yes	Yes	Yes	Yes
City controls	Yes	Yes	Yes	Yes
Constant	−7.45** (3.18)	−6.85** (3.08)	−9.05** (4.34)	−10.97** (4.29)
Year FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Observations	2646	2826	2412	2505

Notes: Standard errors clustered at the city level are shown in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% confidence levels, respectively. FE, fixed effects.

Table 9
The nonlinear effects of broadband speed.

	(1)	(2)
	Total patent applications	
log(Broadband speed)	−1.07 (0.68)	−0.97 (0.63)
log (Broadband speed) squared	0.41*** (0.15)	0.35** (0.14)
Controls	No	Yes
Year FE	Yes	Yes
City FE	Yes	Yes
Constant	1.99** (0.81)	1.06 (3.61)
F test of that coefficients on log*(Broadband speed) and* log*(Broadband speed) squared are jointly equal to 0*	8.59	6.52
p-value	0.00	0.00
Observations	822	822
R-squared	0.25	0.35

Notes: Standard errors clustered at the city level are shown in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% confidence levels, respectively. FE, fixed effects.

higher Internet penetration, GDP per capita, technology investment, and FDI. For different types of patents, we find that increased broadband speeds promote invention and utility model patenting but not design patents, which is consistent with the finding of [41] showing that broadband access does not promote the granting of corporate design patents. There are two potential reasons why the results regarding design patents are not significant. First, the variance of design patents is much smaller than that of other patents, indicating that the variation in design patents is small (Table 1). Therefore, it may be difficult to identify the effect of Internet speed on design patents using a fixed effects model. The second reason may be due to the low knowledge intensity of design innovation. Therefore, the benefits of reduced information costs resulting from increased broadband speeds may be minimal for design innovation.

Furthermore, we use the data from Chinese listed companies to identify one of the impact mechanisms whereby broadband speed drives innovation by facilitating joint patenting between firms. Theoretically, the increase in broadband speed may facilitate video meetings or voice calls between different firms, reduce the inhibition of cooperation because of distance, lower coordination costs, and contribute to the willingness of firms to collaborate on innovation. [14] verified another main impact mechanism through theoretical modeling derivations: Broadband speed may facilitate patenting by reducing information costs. We suggest that the identification of various possible mechanisms for broadband speed to promote innovation and its comparison need to be empirically tested by future studies.

In addition, we examine whether the effect of broadband speed on innovation is nonlinear by adding the squared term of speed to the baseline model. Although the coefficient associated with the square of broadband speed is positive and significant, the coefficient associated with broadband speed is insignificant. Thus, we do not find diminishing returns of broadband speed on innovation, which is inconsistent with the decreasing result found by [14]. There are three possible reasons for this result. First, China's broadband speed is still relatively low compared to that of the United States. In our sample, the maximum urban broadband speed in China during 2015–2017 was 30.39 Mbps, with a mean value of 9.01 Mbps. In comparison, the sample in [14] shows that in 2013, the mean percentage of the population with connection speeds of 10 Mbps, 25 Mbps, 50 Mbps, and 100 Mbps in 2946 counties in the United States were 0.90, 0.52, 0.47, and 0.31, respectively. We suggest that this may be one of the reasons why our study finds no evidence of diminishing returns to innovation for broadband speed. Second, considering differences in institutions, market environments, and levels of development, China, as an emerging country, may differ from developed countries in the utilization of broadband speed. [6] found an inverted U-shaped curve for the impact of broadband speed on economic growth and suggested that the speed threshold (the highest point of return to innovation for broadband) varies across countries and over time. [6] further explained that differences in speed thresholds might be due to differences in the "readiness" of different economies to translate the quality of infrastructure into economic outcomes. We suggest that the "readiness" of China is different from that of the United States. Third, this paper measures urban innovation using the total number of patent applications, including applications for invention, utility model, and design patents.

[14] measured innovation using the number of utility model patents granted. Therefore, the scope of innovation measured in this paper is broader, which may explain why our findings differ from those of [14].

Our findings have important implications for government policies in the improvement of broadband speed. First, our study finds that the innovation promotion of increasing broadband speeds is more substantial in regions with higher GDP per capita, Internet penetration, technology investment, and FDI. Based on an efficiency perspective, policymakers can maximize their role in driving innovation if they reinforce policies to boost broadband speeds in these regions. However, such policies may also lead to the risk of increasing spatial disparities. Based on equity considerations, governments should invest and build more in places where broadband infrastructure is of a lower quality. Thus, the government should consider the trade-offs between equity and efficiency. Second, our study finds no diminishing effect of broadband speed. The policy implication of our findings is that emerging countries such as China can still exploit the dividends of promoting innovation by increasing broadband speeds. Generally, emerging countries may not need to worry prematurely about the risk of declining returns to broadband speeds for innovation at this relatively early stage of broadband development. Third, our findings show that broadband speed improvement has a relatively weak effect on promoting corporate patent collaboration. We suggest that policymakers should develop policies to enable firms to better leverage faster broadband speed for innovation.

Our study has some limitations. First, our data cannot distinguish between fixed and mobile broadband, which may have different implications for innovation. Especially in emerging countries such as China, where mobile broadband started late but is growing rapidly, the role of mobile broadband is already prominent. Future research may further explore the similarities and differences in the impact of mobile broadband speed and fixed broadband speed on innovation. Second, due to the data accessibility of broadband speed at the city level, the data sample used in our study is limited to 2015–2017, which may limit the potential generalizability of our findings. Although we extend the research sample period (to 2011–2018) in our robustness check with the "Broadband China" pilot city policy to evaluate the policy shock for broadband speed improvement, such a measurement does not directly measure Internet speed. Future research may examine the relationship between broadband speeds and innovation over a more extended sample period when data are abundant and available. In addition, the lack of relevant data on information costs at the city or firm level prevents us from examining the mechanisms that reduce information costs in detail in this study. Other mechanisms for the effect of broadband speed on innovation may be possible. Future research could consider simultaneously testing and comparing the information costs, cooperation, and other mechanisms.

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Appendix A

Table A1
Descriptive statistics for Table 5

	Observations	Mean	Standard deviation	Min	Max
Dependent variables					
Total patent applications per *10,000 people, 2012–2019*	2240	1.39	1.97	0.02	17.28
Total patent applications per *10,000 people, 2013–2020*	2240	1.42	1.99	0.02	18.51
Independent variable					
Broadbandcity equals to 1 if the city has implemented the pilot policy, 0 otherwise	2240	0.19	0.39	0.00	1.00
City-level characteristics, 2011–2018					
log*(GDP* per capita*)*	2240	10.66	0.55	8.80	11.83
Ratio of secondary industry output to GDP	2240	47.12	10.15	14.39	89.34
Share of fiscal expenditures on science and technology	2240	1.60	1.46	0.07	13.09
log*(FDI)*	2240	5.35	1.95	−5.62	8.95
Internet penetration	2240	19.04	11.06	2.66	109.84
Having at least one high-speed railway station	2240	0.52	0.50	0.00	1.00
Commodity house price	2240	5.02	3.21	1.39	47.94
log*(Number of higher education institutions in the city)*	2240	1.41	1.11	−0.29	4.19

Table A2
Descriptive statistics for mechanism analysis

	Observations	Mean	Standard deviation	Min	Max
Joint patenting of firms					
Firm's patent applications, 2016–2018	7086	3.54	13.62	0.00	115.00
Firm's patent granted, 2016−2018	7086	2.19	8.74	0.00	82.00
Firm's patent applications, 2017–2019	7086	4.20	15.78	0.00	132.00

(*continued on next page*)

Table A2 (*continued*)

	Observations	Mean	Standard deviation	Min	Max
Firm's patent granted, 2017–2019	7086	2.51	9.78	0.00	89.00
Independent variable					
City's broadband speed, 2015–2017	7086	11.23	5.14	3.79	30.39
Firm-level characteristics, 2015–2017					
Firm's age	7086	17.60	5.32	4.50	49.50
Percentage of employees with a bachelor's degree or higher education (%)	7086	28.33	20.26	0.00	114.95
Return on total assets (%)	7086	3.78	6.09	−223.81	48.19
Leverage ratio (%)	7086	42.05	20.21	3.08	98.70
log*(total assets)*	7086	22.30	1.27	19.89	26.17
log*(total employees)*	7086	7.74	1.24	4.72	11.16
City-level characteristics, 2015–2017					
log*(GDP* per capita*)*	7086	11.39	0.45	9.69	11.83
Ratio of secondary industry output to GDP	7086	42.63	7.40	17.75	84.09
Share of fiscal expenditures on science and technology	7086	3.65	1.89	0.07	12.65
log*(FDI)*	7086	7.53	1.66	−3.91	8.91
Internet penetration	7086	30.74	9.86	6.73	88.93
Having at least one high-speed railway station	7086	0.92	0.27	0.00	1.00
Commodity house price	7086	12.40	9.14	2.52	45.15
log*(Number of higher education institutions in the city)*	7086	2.92	1.17	0.00	4.19

Appendix B

Considering that causal identification based on "Broadband China" pilot cities policy can only be valid if the common trend assumption holds, we estimate the following model:

$$Innovation_{i,t=}\lambda_0 + \lambda_1 Before^2_{i,t-1} + \lambda_2 Before^1_{i,t-1} + \lambda_3 Current_{i,t-1} + \lambda_4 After^1_{i,t-1} + \lambda_5 After^2_{i,t-1} + \lambda_6 After^{3+}_{i,t-1} + \lambda_7 X_{i,t-1} + \rho_i + \pi_t + o_{i,t} \ ,$$

where $Before^2$ and $Before^1$ represent the second year and first year prior to the event year, $After^1$, $After^2$, and $After^{3+}$ denote the first, second, and third year after, respectively, and *Current* is the event year. All other variables share the same definitions as those introduced in Eq. (1). We present the estimation results in Figure B1. We observe a statistically insignificant coefficient estimation of $Before^2$ and $Before^1$, which suggests that the parallel trend test supports a causal interpretation.

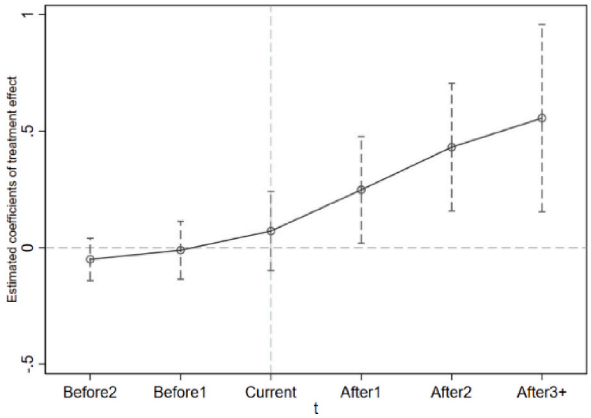

Figure B1. A parallel trend test on the "Broadband China" pilot cities policy.

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