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Digital Infrastructure and the Network Embeddedness of Peripheral Regions: Evidence from Intercity Patent Collaboration in China

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ABSTRACT: Using intercity co-patenting data for Chinese cities from 2010 to 2022, this study examines how digital infrastructure shapes intercity innovation collaboration involving peripheral regions. The results show that digital infrastructure significantly strengthens intercity collaborative patenting between peripheral and core cities, enabling peripheral regions to become more deeply embedded in innovation networks. Further analyses suggest that digital infrastructure eases market frictions in cross-regional collaboration and improves institutional coordination, thereby strengthening the conditions under which peripheral regions benefit from digital connectivity. These findings highlight the role of digital infrastructure in reshaping interregional innovation linkages involving peripheral regions.

Keywords: Digital infrastructure; Innovation collaboration; Peripheral regions; Network embeddedness

1. Introduction

Over the past decade, the rapid expansion of digital technologies has reshaped the spatial organization of innovation activities (Autio et al., 2018; Gul & Euchner, 2019). Unlike traditional infrastructure, digital infrastructure is defined by high connectivity and dense data flows (Verfürth & Helwing-Hentschel, 2025; H. Li & Gao, 2026), which ease spatial frictions and make knowledge exchange across regions increasingly feasible. As innovation becomes less reliant on physical proximity, relationships between regions are increasingly organized through inter-urban networks rather than simple geographic closeness, altering how regions interact within broader innovation systems.

At the same time, innovation remains a key driver of regional development, but

its benefits are distributed very unevenly across space (Breese, 1975; Cooke, 1992; Grillitsch & Nilsson, 2015). Peripheral regions, in particular, continue to face persistent constraints, including limited local knowledge bases and weaker institutional capacity, which shape both the scale and the intensity of their innovative activities(Shearmur, 2015; Pugh & Dubois, 2021). In this context, intercity innovation collaboration has become an important channel through which peripheral regions engage with wider innovation networks. Through collaboration with external partners, peripheral regions can gain access to heterogeneous knowledge, pursue more diversified technological trajectories and reduce their dependence on local capabilities (Meili & Shearmur, 2019; Santoalha, 2019; Straccamore et al., 2023). The ability of peripheral regions to effectively absorb technological inflows from core areas is therefore central to narrowing regional innovation disparities and to improving the overall structure of intercity innovation networks.

Digital infrastructure has attracted growing attention as a potential means of reshaping uneven innovation geographies. By lowering information and coordination costs, improved digital connectivity can facilitate collaboration between geographically distant actors within intercity innovation networks (Agrawal & Goldfarb, 2008; Ding et al., 2010; Forman & van Zeebroeck, 2012; H. Li & Gao, 2026). Related work on physical infrastructure has likewise shown that improvements in interregional connectivity-through highways, rail and other transport networks-reshape the spatial pattern of inventive collaboration (Agrawal et al., 2017; Catalini et al., 2020). However, digitalization may also reinforce existing spatial hierarchies. Core regions often gain earlier access to advanced digital infrastructure and benefit from stronger absorptive capacity and more developed innovation ecosystems, which can amplify cumulative advantages. While numerous literature links digital infrastructure to regional innovation, much of this work focuses on local innovation outputs or aggregate patterns of technology diffusion (Czernich et al., 2011; Forman et al., 2012; B. Li, 2025). Less attention has been paid to how digital infrastructure shapes the network embeddedness of peripheral regions within inter-urban innovation networks, particularly through collaborative innovation between peripheral and core

cities.

This study examines the relationship between digital infrastructure and intercity innovation collaboration involving peripheral regions. Adopting a network perspective, we focus on collaborative ties between peripheral and core cities and assess whether digital infrastructure alters the network embeddedness of peripheral regions by shaping their access to external knowledge and participation in inter-urban innovation networks. In doing so, the study shifts attention from innovation outcomes measured in isolation to the relational position of peripheral regions within innovation networks.

Our study makes three potential contributions. First, We bring a network perspective to the analysis of digital infrastructure and peripheral regional development by focusing explicitly on intercity innovation collaboration between peripheral and core cities. Drawing on a comprehensive set of intercity co-invention patent records covering Chinese cities, the study enables an examination of collaborative ties involving peripheral regions, moving beyond evidence based on listed firms or specific market segments (Belderbos et al., 2004; Bruneel et al., 2010).

Second, beyond establishing whether digital infrastructure matters, the study examines how it matters. Combining market mechanisms and institutional coordination, we explore two channels through which digital infrastructure may shape intercity innovation collaboration in peripheral regions. By reducing market frictions, digital infrastructure lowers the costs of search, matching and coordination. By enhancing institutional capacity, it improves governance effectiveness and reduces institutional uncertainty faced by external collaborators.

Third, the study shows that the positive role of digital infrastructure is reinforced by supportive institutional arrangements. Stronger intellectual property protection and increased R&D subsidies amplify the effect of digital infrastructure in promoting intercity innovation collaboration between peripheral and core cities, strengthening the integration of peripheral regions into wider innovation networks.

These contributions are supported by an empirical analysis. Using approximately 520,000 intercity co-patent records from China between 2010 and 2022, our findings

show that digital infrastructure significantly strengthens technological collaboration between peripheral and core cities, thereby enhancing the network embeddedness of peripheral regions within regional innovation networks. Mechanism analysis shows that digital infrastructure enhances the network embeddedness of peripheral regions by reducing market frictions and improving institutional capacity. Moreover, supportive institutional arrangements, such as stronger intellectual property protection and increased R&D subsidies, reinforce the positive role of digital infrastructure in facilitating intercity innovation collaboration.

The remainder of the study is organized as follows. Section 2 reviews the related literature and outlines the framework. Section 3 describes the data and empirical strategy. Section 4 presents the results and additional analyses. Section 5 concludes.

2. Digital infrastructure and intercity innovation collaboration

2.1 Peripheral regions and innovation networks

Research on innovation collaboration has predominantly focused on cities, emphasising factors such as economic scale, technological capacity, geographic proximity and the structure of local innovation systems (Bathelt et al., 2004; Broekel et al., 2017; Florida et al., 2017). This literature has contributed substantially to understanding how collaborative ties between cities emerge and persist within inter-urban innovation networks. However, it often frames innovation as an activity centred on core urban areas, with peripheral regions appearing mainly as secondary or residual spaces. As Glückler et al.(2023) notes, innovation in peripheral regions has received comparatively limited systematic attention. This relative neglect does not imply an absence of innovative activity. In many cases, early-stage innovation depends less on immediate market demand than on experimentation, learning and the availability of specific skills (Dosi, 1982; Cohen & Levinthal, 1990; Aghion et al., 2016). Lower production and living costs can therefore make some peripheral regions suitable locations for such activities, particularly when innovation outcomes are uncertain or slow to materialize.

Peripheral regions are not isolated from wider innovation systems (Balland & Boschma, 2021; Glückler et al., 2023). Firms and organizations in these regions often maintain collaborative ties beyond their immediate surroundings, including intercity partnerships, supplier relationships and participation in broader production and innovation networks. Such connections can provide access to external knowledge and resources, even when local innovation environments remain limited. However, access to external connections does not necessarily translate into strong positions within innovation networks. Peripheral regions often remain at a disadvantage, a pattern commonly discussed in the literature on agglomeration and localized spillovers (Bathelt et al., 2004; Boschma, 2005). In practice, innovative firms originating in peripheral areas frequently relocate parts of their activities to core cities or establish branches there, weakening local knowledge accumulation and reinforcing uneven network positions over time.

In this context, understanding innovation in peripheral regions requires attention to cross-regional connections rather than local conditions alone. When local innovation environments are limited, firms often rely on collaboration with partners in core cities or on access to knowledge and services located elsewhere. What matters in these arrangements is not only local innovation capacity, but also whether collaboration can be organized effectively across space (Fitjar & Rodríguez-Pose, 2011; Grillitsch & Nilsson, 2015). Digital infrastructure is directly relevant in this regard, as it shapes the costs and feasibility of information exchange and coordination, and thus influences how intercity collaborative ties are formed and sustained.

2.2 Digital infrastructure and market frictions

Interregional innovation collaboration depends on knowledge exchange within intercity innovation networks. Because the stock of knowledge available within any single region is limited over the long run, sustained innovation increasingly depends on access to technology, information, skills and other resources originating outside the region(Bathelt et al., 2004; Grillitsch & Nilsson, 2015). For peripheral regions, such access is particularly important, as local innovation activities often depend on cross-regional cooperation to compensate for weaker agglomeration effects and more

limited innovation environments.

At the same time, intercity innovation collaboration is associated with substantial market frictions, including search, matching and coordination costs (Bathelt et al., 2004; Ascani et al., 2020). Innovation actors in peripheral regions frequently face pronounced information asymmetries when identifying potential collaboration partners in other cities, as well as heightened uncertainty regarding partners' technological capabilities, organizational stability and the expected outcomes of collaboration. Even when cross-regional cooperation may generate potential benefits, these market frictions can reduce the likelihood that collaboration within inter-urban innovation networks is initiated or sustained (Galaso & Kovářík, 2021; Vivona et al., 2023).

Collaboration as an important channel through which peripheral regions connect to external sources of knowledge and become embedded in wider innovation networks (Balland et al., 2019; Ascani et al., 2020). Contract-based or institutionally supported partnerships enable innovation actors to overcome constraints related to geographic distance and limited local knowledge bases, allowing them to establish and maintain collaborative ties beyond their immediate surroundings. Technology transfer and talent mobility provide additional pathways for introducing external knowledge and experience(Cantner et al., 2019), supporting innovation activities that are not fully dependent on local research and development conditions.

Digital infrastructure can shape these processes by influencing how information is exchanged and how collaboration is organized within intercity innovation networks. By improving the efficiency of cross-regional information exchange, digital infrastructure can ease search and matching frictions in innovation collaboration (Y. Li et al., 2025; H. Li & Gao, 2026). Enhanced digital connectivity allows innovation actors to access information on potential partners' technological profiles, organizational characteristics and prior collaboration experience through online platforms and digital networks (Zeng & Tao, 2025), thereby lowering information costs and facilitating partner selection. Digital technologies also affect coordination during collaborative activities. Cloud-based platforms and remote communication

tools make it easier for geographically dispersed partners to sustain regular interaction and timely feedback (Sun & Li, 2025). For peripheral regions that have traditionally faced disadvantages in coordinating with distant innovation centres, such tools can reduce the constraints imposed by spatial distance on collaborative processes.

Intercity innovation collaboration is frequently embedded in cross-regional production and supply-chain relationships, particularly when peripheral regions engage with technologically leading core firms (Grillitsch & Nilsson, 2015; Zeng & Tao, 2025). Digital infrastructure supports information sharing and coordination along these inter-urban linkages, reducing uncertainty in related transactions and facilitating access to external technological and knowledge resources (Straccamore et al., 2023; B. Li, 2025). In this respect, the role of digital infrastructure resembles that of transport infrastructure in improving accessibility, although its effects operate primarily through information exchange and coordination rather than physical movement. In this respect, digital infrastructure lowers market frictions related to search, matching and coordination, making it easier for peripheral regions to participate in intercity innovation networks.

Hypothesis 1: Digital infrastructure promotes innovation collaboration in peripheral regions by reducing market frictions.

2.2 Digital infrastructure and institutional capacity

Beyond market frictions, intercity innovation collaboration is also shaped by institutional conditions and governance capacity within inter-urban innovation networks. Compared with core cities, peripheral regions often operate under less efficient administrative systems and more uneven policy implementation (Tödtling & Trippl, 2005; Sun & Li, 2025). While weaker institutional capacity does not necessarily constrain local innovation activities in isolation, it can become a more significant obstacle in cross-regional collaboration, where institutional uncertainty plays a larger role in shaping cooperation decisions across cities.

For potential collaborators, institutional capacity matters less in terms of the scale of policy support than in the clarity, consistency and reliability of rules and

procedures (Gulen & Ion, 2016). When project approval processes, funding arrangements, intellectual property protection or regulatory enforcement are perceived as unclear or inconsistently applied, intercity innovation collaboration may be discouraged by institutional risk, even when technological complementarities between regions are strong (Nalmpanti et al., 2024). Peripheral regions, which typically possess less institutional depth and more limited governance experience, are therefore more exposed to such constraints when attempting to establish and maintain collaborative ties with external innovation partners.

Digital infrastructure provides an important channel through which these institutional conditions may be improved. By supporting data integration, more standardised administrative procedures and the provision of digital public services, digital tools can reduce information asymmetries and discretionary practices in governance (Benner & Tushman, 2003; Goldfarb & Tucker, 2019). The use of data records and traceable processes makes administrative actions easier to monitor and review, which can enhance consistency over time and reduce uncertainty for external actors engaging in intercity innovation collaboration. Rather than implying more intensive intervention, digitalization may contribute to a governance environment that is clearer, more transparent and more predictable.

Digital tools may also ease coordination problems associated with administrative fragmentation across jurisdictions. Through data sharing among departments and across cities, digital platforms can facilitate coordination in innovation-related activities such as research project administration, technology service matching and regulatory alignment (Gawer & Cusumano, 2014). By simplifying information standards and shortening communication channels, these arrangements can lower the institutional frictions that often arise in inter-urban collaboration (B. Wang et al., 2022). For external partners, improved institutional compatibility reduces the perceived risks of working with peripheral regions and supports the formation of more stable collaborative relationships. By strengthening governance capacity, digital infrastructure provides a more stable and predictable basis for peripheral regions to engage in intercity innovation collaboration and to improve their position within

innovation networks.

Hypothesis 2: Digital infrastructure promotes innovation collaboration in peripheral regions by enhancing institutional capacity.

3. Data and methodology

3.1 Empirical strategy

This study examines the causal effect of digital infrastructure on intercity innovation collaboration involving peripheral regions. Empirically identifying this effect is challenging because the deployment of digital infrastructure is closely intertwined with a range of regional characteristics that also shape participation in inter-urban innovation networks. Economic development, institutional capacity and local technological conditions are all likely to influence both the expansion of digital infrastructure and the observed patterns of innovation collaboration between cities. Moreover, these factors may interact in complex and potentially non-linear ways, affecting how peripheral regions position themselves within innovation networks. As a result, isolating the effect of digital infrastructure on intercity innovation collaboration using standard linear regression approaches is difficult.

Conventional parametric models rely on strong assumptions regarding functional form and the structure of variable interactions. In the present context, such assumptions are difficult to justify and may result in biased estimates when the underlying relationships are misspecified. To address these concerns, we adopt a Double Machine Learning (DML) framework (Chernozhukov et al., 2018). DML is not an instrumental-variables estimator and does not require an external instrument. Rather, it is a partially linear model in which the relationships between the high-dimensional control variables and both the outcome and the treatment are estimated using flexible machine learning methods, while the parameter of interest is recovered through an orthogonalized moment condition. This separation between the estimation of confounding relationships and the estimation of the parameter of interest reduces sensitivity to functional-form misspecification, and the orthogonalization step mitigates the orthogonalization bias that would otherwise arise when machine

learning methods are used in the nuisance step (Storm et al., 2020; Yang et al., 2020). The framework is well suited to settings, such as the present one, where smart city pilot designation is shaped by a large set of city characteristics and where the functional form linking these characteristics to collaborative innovation is not known a priori.

Accordingly, we consider a partially linear model of the form:

$$Y_{it+1} = \theta_0 D_{it} + g\left(X_{it}\right) + U_{it} \tag{1}$$

With the identifying condition

$$E\left[U_{it} \mid D_{it}, X_{it}\right] = 0 \tag{2}$$

Here, i indexes cities and t denotes years. Y_{t+1} is the level of inter-city collaborative innovation in city i in year $t+1$. D_{it} is the digital infrastructure indicator, defined as a policy-related treatment variable that takes the value of one after the implementation of the smart city initiative and zero otherwise. The parameter θ_0 captures the causal effect of digital infrastructure on collaborative innovation in peripheral regions. X_{it} is a vector of control variables, whose influence on the outcome is captured by the unknown function $g(\cdot)$, and U_{it} is an error term.

Direct estimation of equation (1) may lead to biased estimates of θ_0 in finite samples, as regularisation bias can arise when flexible methods are used to approximate the unknown function $g(X_{it})$. To address this issue, we introduce an auxiliary equation for the treatment variable:

$$D_{it} = m\left(X_{it}\right) + V_{it} \tag{3}$$

with

$$E\left[V_{it} \mid X_{it}\right] = 0 \tag{4}$$

The function $m(X_{it})$ captures the relationship between the treatment variable and the high-dimensional set of controls. Because its functional form is unknown, we estimate $m(\cdot)$ using machine learning methods. Based on this estimation, we obtain the residualised treatment variable $\hat{V}_{it} = D_{it} - \hat{m}\left(X_{it}\right)$.

Using the orthogonalisation principle of the DML approach, the residual is then

used to identify the causal effect of digital infrastructure. Specifically, the estimator of θ_0 is given by:

$$\hat{\theta}_0 = \left(\frac{1}{n} \sum_{i \in I, t \in T} \hat{V}_{it} D_{it} \right)^{-1} \left(\frac{1}{n} \sum_{i \in I, t \in T} \hat{V}_{it} \left(Y_{it+1} - g\left(\hat{X}_{it} \right) \right) \right), \tag{5}$$

In practice, both nuisance functions $g(X_{it})$ and $m(X_{it})$ are estimated using machine learning algorithms such as Random Forest and Lasso. City and year fixed effects are included to account for time-invariant city characteristics and common temporal shocks. This procedure allows us to obtain a consistent estimate of the causal effect of digital infrastructure while remaining agnostic about the functional form of the confounding relationships.

3.2 Data and variable

3.2.1 Core and peripheral cities

The distinction between core and peripheral cities is central to the analysis, as it defines the structure of intercity innovation networks examined in this study. Following(Yu et al., 2019), municipalities directly under the central government, provincial capitals and sub-provincial cities are initially classified as core cities, as these cities typically concentrate technological and industrial resources and occupy leading positions within regional innovation systems.

Administrative status, however, does not always correspond to actual economic or technological centrality within inter-urban innovation networks (Breschi & Lissoni, 2009). To account for this discrepancy, cities whose economic scale or technological capacity substantially exceeds that of the provincial capital during the sample period are also classified as core cities. All remaining prefecture-level cities are accordingly defined as peripheral cities. This classification captures differences in functional centrality and network position rather than relying solely on administrative hierarchy, and is therefore better suited to analysing collaborative innovation between peripheral and core regions.

3.2.2 Dependent variable

The dependent variable measures the level of intercity innovation collaboration

between peripheral and core cities. It is defined as the number of invention patents jointly applied for by peripheral and core cities in a given year, capturing the intensity of collaborative ties linking peripheral regions to the core of the inter-urban innovation network.

Data on co-invented patents are obtained from the China Patent Database, which provides comprehensive records of invention patent applications in mainland China since 1985, including information on application dates, applicants and their registered addresses. The construction of the collaboration measure proceeds in three steps. First, using patent publication numbers, we identify invention patents filed between 2010 and 2022 that involve at least two applicants. Patents are excluded when one applicant is located in Hong Kong, Macao, Taiwan or overseas. This procedure yields approximately 520,000 intercity co-patent records; Second, applicants are assigned to prefecture-level cities based on their registered addresses. When applicants are located in different cities, the patent is classified as an intercity collaborative innovation outcome. For patents involving three or more applicants from different cities, all possible city-pair combinations are constructed; about 17% of collaborative patents fall into this category. Third, we retain only city-pair combinations in which one city is classified as peripheral and the other as a core city. For each peripheral city, the number of jointly applied invention patents with all core cities is aggregated at the city-year level and used as the dependent variable in the analysis.

3.2.3 Independent variable

As information technologies such as the internet, big data and cloud computing have diffused, digital infrastructure in China has evolved from fragmented technical investments into more integrated, city-level systems. Within this process, smart city initiatives represent a platform-based form of digital infrastructure that integrates broadband networks, urban data platforms, and digital public services into a unified digital foundation (Wang et al., 2022).

China’s National Smart City Pilot programme was launched by the Ministry of Housing and Urban-Rural Development (MoHURD) in 2012 and expanded through three successive batches of approvals in 2012, 2013 and 2014. Cities applied for

designation and were evaluated by MoHURD on a combination of criteria including local administrative capacity, existing digital infrastructure, fiscal resources, and proposed plans for urban informatization (Wu et al., 2023). Designated cities were required to develop integrated digital systems covering broadband networks, urban operating data platforms, and digital public services, and to report progress against pilot benchmarks. Designation was therefore not a standalone subsidy but a substantial commitment of administrative attention and local fiscal resources to the integration of digital infrastructure across municipal functions. Importantly, the formal selection criteria did not include the attraction of inventors or research-active firms. Accordingly, we construct a binary variable based on the smart city pilot policy: a peripheral city takes the value of one if it is approved as a smart city pilot in or before year t, and zero otherwise. Of the 248 peripheral cities in our sample, 88 received pilot designation during the sample period; the remainder serve as the comparison group.

3.2.4 Control variables

To isolate the effect of digital infrastructure on intercity innovation collaboration involving peripheral regions, we include a set of control variables capturing regional economic and innovation fundamentals. These controls account for differences in economic development, innovative capacity and local institutional resources across cities, all of which may shape participation in inter-urban innovation networks. Specifically, the control variables include GDP per capita, local innovation capacity, financial depth, the fiscal capacity of local governments and industrial structure.

All variables are constructed from the China City Statistical Yearbook and the CSMAR database. The China City Statistical Yearbook is the official source of city-level economic indicators published by China's National Bureau of Statistics. CSMAR (China Stock Market & Accounting Research) is a widely used commercial research database aggregating firm-level data, and is the important data source for empirical studies on Chinese listed firms. Descriptive statistics are reported in Table 1.

Table 1. Descriptive statistics

variables	Mean	Std	Max	Min
Innovation collaboration (Inncol)	0.380	0.874	0	12.56
Digital infrastructure (D)	0.274	0.446	0	1.000
Economic development	10.657	0.566	8.576	12.579
Innovation capacity	7.151	1.492	2.303	11.575
Financial development	16.224	0.903	13.318	19.092
Fiscal capacity	14.745	0.619	11.711	16.842
Industrial structure	40.348	8.656	9.760	73.890
Market frictions	0.566	0.814	0	3.332
Institutional capacity	0.246	0.431	0	1.000

3.3 Descriptive patterns of intercity collaboration

Figure 1 depicts the spatiotemporal evolution of intercity innovation collaboration between peripheral regions and core cities from 2010 to 2022. Two broad patterns stand out. First, the overall intensity of collaborative innovation increases markedly over time. In the early years of the sample period, collaborative ties are relatively sparse and largely concentrated in eastern coastal regions. As time progresses, however, a growing number of peripheral cities in central and western China become involved in intercity innovation collaboration, indicating a gradual widening of participation within the inter-urban innovation network.

Second, the spatial reach of collaboration expands alongside this increase in intensity. Peripheral regions increasingly establish collaborative linkages with multiple core cities, moving beyond predominantly local or neighbouring partnerships. Although the total number of collaborative invention patents exhibits a modest decline toward the end of the sample period, the number of participating cities remains relatively stable. This pattern suggests that intercity collaboration has become more persistent, with established collaborative ties continuing to operate within the innovation network rather than being replaced by sporadic or one-off interactions. These descriptive patterns point to a gradual broadening and consolidation of intercity innovation networks involving peripheral regions. They provide background context for the empirical analysis that follows, which examines how digital infrastructure shapes intercity innovation collaboration and the network embeddedness of peripheral regions.

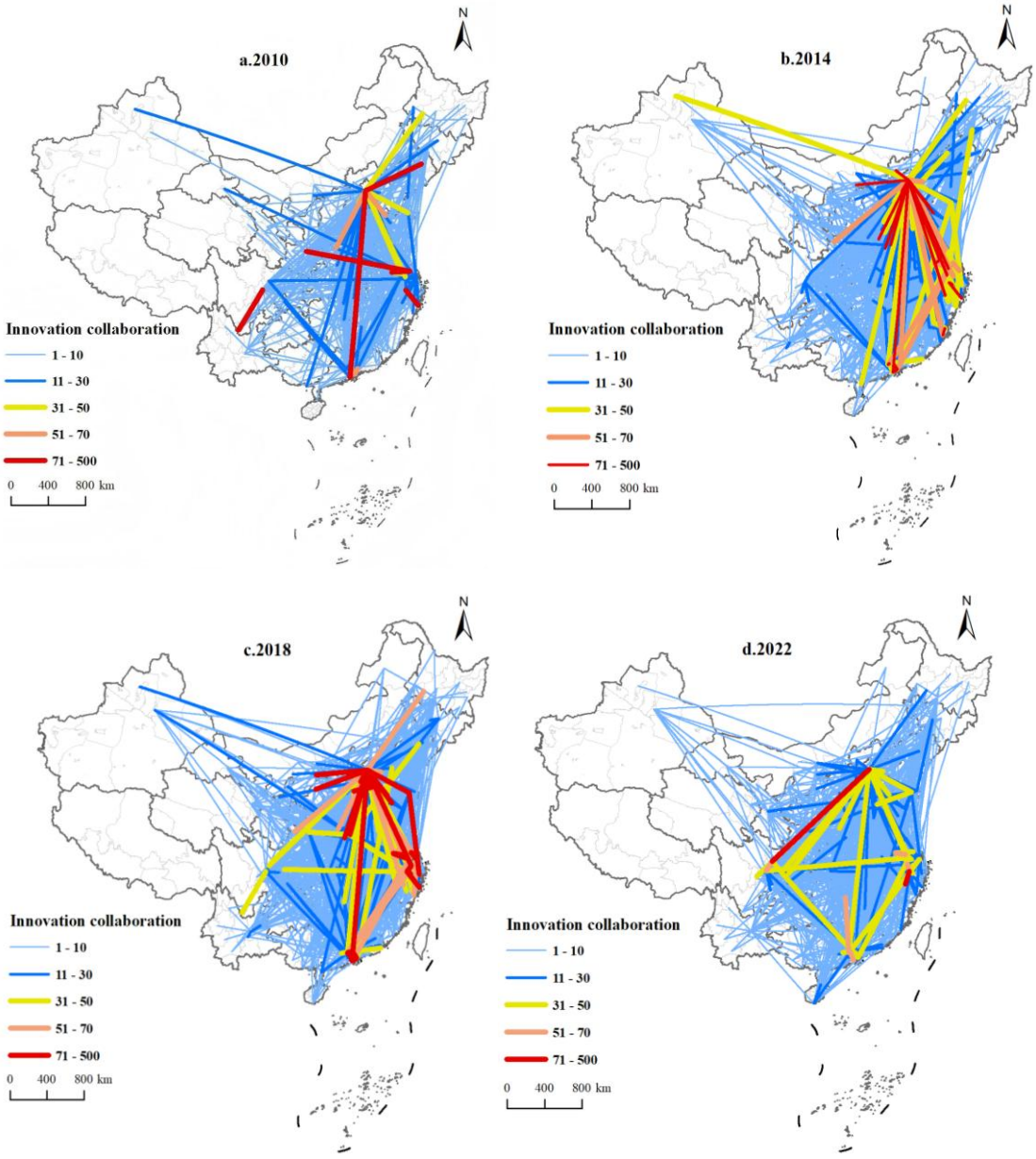


Figure 1. Number of collaborative innovation city pairs and patents

Note: This map is based on the standard map produced by the Map Technical Review Center of the Ministry of Natural Resources (Review No. GS (2023) 2767).

4. Empirical results

4.1 Baseline results

Table 2 reports the baseline estimates of the impact of digital infrastructure on intercity innovation collaboration involving peripheral regions. Column (1) presents results from the baseline DML specification, which controls for city and year fixed effects while accounting for high-dimensional confounding factors. The estimated

coefficient on digital infrastructure is positive and significant at the 1% level. This result suggests that participation in the smart city pilot programme is associated with more intensive collaborative patenting between peripheral regions and core cities. And the finding is consistent with the argument developed earlier: enhanced digital connectivity reduces spatial and informational barriers, making it easier for peripheral regions to establish and sustain collaborative ties with core cities and to access external technological knowledge within inter-urban innovation networks.

Columns (2) and (3) examine the sensitivity of the baseline results to alternative functional form assumptions. Although the DML framework already allows for nonlinear relationships through machine learning algorithms, we further include first-order and second-order terms of key control variables in the regression. The estimated effects of digital infrastructure remain stable in both magnitude and statistical significance, indicating that the baseline results are not driven by functional form misspecification. For comparison, Column (4) reports estimates from a conventional difference-in-differences (DID) specification. The coefficient obtained from the DID model is comparable in both size and significance to the DML estimate. The consistency across these empirical strategies suggests that the positive association between digital infrastructure and intercity innovation collaboration is robust and not sensitive to the choice of estimation method. The baseline results provide clear empirical evidence that digital infrastructure strengthens collaborative innovation between peripheral regions and core cities. In doing so, it facilitates the integration of peripheral regions into intercity innovation networks, supporting the argument that digital infrastructure shapes the conditions under which peripheral regions become more deeply embedded within regional innovation systems.

Table 2. Baseline regression results

	(1)	(2)	(3)	(4)
Variables	Inncol	Inncol	Inncol	Inncol
D_{it}	0.111***	0.103***	0.102**	0.110**
	(0.041)	(0.040)	(0.040)	(0.045)
Constant	-0.001	0.000	0.000	-2.200***
	(0.009)	(0.009)	(0.009)	(0.801)
Control	No	Yes	No	No
Control^2	No	No	Yes	Yes

N	3224	3212	3212	3212
Method	LassoCV	LassoCV	LassoCV	OLS
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Notes: *, *, and *** represent significance at the 10%, 5%, and 1% levels, respectively; robust standard errors are reported in parentheses. The same applies below.

4.2 Robustness checks

To further assess the reliability of the baseline findings, we conduct a series of robustness checks. First, to reduce the potential influence of extreme observations, we apply a 1% bilateral trimming to the key continuous variables. As shown in Column (1) of Table 3, the estimated effect of digital infrastructure on intercity innovation collaboration remains positive and statistically significant. Second, we account for unobserved province-level factors that may vary over time by including province-by-year fixed effects, Column (2) shows that the estimated coefficient on digital infrastructure remains stable in significance. This result indicates that provincial trends, such as regional policy shifts or macroeconomic conditions, do not explain the observed relationship between digital infrastructure and collaborative innovation involving peripheral regions. Third, we examine the sensitivity of the DML estimates to the choice of machine learning algorithm used in the residualisation stage. Replacing the Lasso estimator with ridge regression Column (3) and support vector regression Column (4) produces qualitatively similar results. The consistency across alternative algorithms indicates that the estimated effect of digital infrastructure on intercity innovation collaboration is not driven by a particular regularisation technique or functional approximation.

Besides, to address concerns that the estimated effect may be confounded by other digital-related policy initiatives implemented during the sample period, we exclude observations affected by the “Broadband China” strategy and the “National Big Data Comprehensive Pilot Zone” policy. The results, reported in Columns (5) and (6), remain consistent with the baseline estimates. These results suggest that the positive association between digital infrastructure and intercity innovation

collaboration involving peripheral regions is not attributable to concurrent digital policy interventions.

Table 3. Robustness test

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	Inncol	Inncol	Inncol	Inncol	Inncol	Inncol
D_{it}	0.069**	0.158***	0.106**	0.179***	0.073*	0.082**
	(0.028)	(0.039)	(0.046)	(0.041)	(0.043)	(0.037)
Constant	0.001	0.001	-0.000	0.140***	0.004	0.001
	(0.006)	(0.009)	(0.009)	(0.012)	(0.011)	(0.008)
Control[2]	Yes	Yes	Yes	Yes	Yes	Yes
N	3212	3212	3212	3212	2598	2912
MLmethods	LassoCV	LassoCV	Ridge	SVM	LassoCV	LassoCV
Pro×Year	No	Yes	No	No	No	No
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes

We further employ a generalized random forest model to estimate the conditional average treatment effects (CATEs) of digital infrastructure on collaborative innovation in peripheral regions (Athey et al., 2019). As shown in Figure 2, the distribution of estimated CATEs remains highly consistent across specifications with 500, 2,000, 4,000, and 8,000 trees, and exhibits a pronounced right-skewed pattern. This suggests that, for the majority of peripheral regions, participation in the smart city pilot programme is associated with a marked increase in collaborative innovation with core cities. Although a small number of observations display negative estimated effects, most CATEs are concentrated in the range between 0.06 and 0.08, with the mean remaining positive across all specifications. From a non-parametric perspective, these results corroborate the robustness of the baseline regression findings and provide further support for the role of digital infrastructure in enhancing collaborative innovation in peripheral regions.

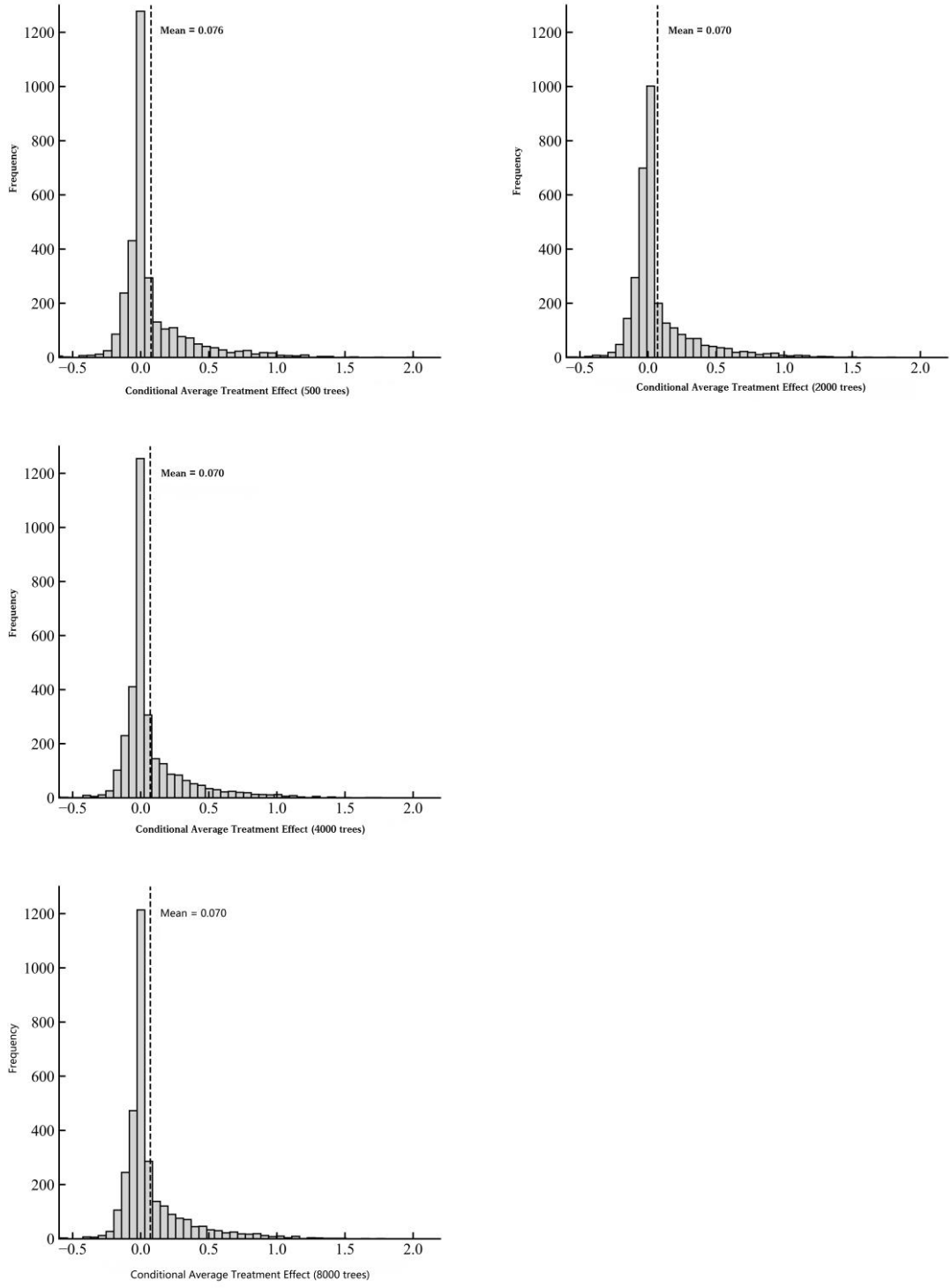


Figure 2. The distributional effects of digital infrastructure on collaborative innovation in peripheral regions

4.3 Mechanism analysis

4.3.1 Market frictions

Market frictions related to search, matching and coordination are a persistent obstacle for peripheral regions seeking to engage in intercity innovation collaboration (Grillitsch & Nilsson, 2015). When information is incomplete and coordination across regions is costly, collaborative ties with core cities are more difficult to establish and sustain. If digital infrastructure reduces these frictions, peripheral regions should face fewer barriers in forming cross-regional economic and innovation linkages.

To capture market connections across regions, we focus on inter-firm supply relationships as a concrete manifestation of cross-regional economic interaction. Using data from the CSMAR database, we identify all listed firms located in peripheral regions and collect information on their top five suppliers during the sample period. Supplier locations are precisely matched using firm identifiers and business registration records, including geographic coordinates. We then retain supplier relationships in which the supplier is located in a core city and construct a panel at the peripheral region–core region–year level to reflect cross-regional supply linkages. Aggregating these relationships to the city-pair level yields a measure of the intensity of market connections between peripheral regions and core cities, which serves as a proxy for market frictions in cross-regional interactions.

Columns (1) and (2) of Table 4 report the corresponding regression results. The estimated coefficients on digital infrastructure are positive and statistically significant. This indicates that improvements in digital infrastructure are associated with lower market frictions faced by peripheral regions in cross-regional interactions. In practical, digital infrastructure appears to facilitate the formation and stability of market connections linking peripheral regions to core cities (Y. Li et al., 2025), thereby reducing the costs of search, matching and coordination. These findings provide empirical support for Hypothesis 1.

4.3.2 Institutional capacity

Limited institutional capacity can heighten uncertainty in administrative procedures, policy implementation, and regulatory enforcement (Tödtling & Trippl, 2005), thereby discouraging potential collaborators from engaging with peripheral regions. In contexts where governance arrangements are fragmented or unclear, firms

face higher institutional transaction costs and greater risks in cross-regional collaboration. If digital infrastructure contributes to strengthening institutional capacity, it should reduce such uncertainty and foster a more predictable and inclusive environment for intercity innovation collaboration.

To capture improvements in institutional capacity associated with digital infrastructure, we focus on the development of digital government practices. In particular, we use the establishment of big data management agencies as an indicator of local digital governance reform. The creation of such agencies reflects efforts by local governments to integrate data resources, adopt digital and intelligent systems in regulatory activities, and enhance coordination across administrative jurisdictions. Through these reforms, digital government initiatives are expected to lower institutional transaction costs, improve the transparency and predictability of policy implementation, and encourage innovation actors to engage in cross-regional collaborative activities.

Columns (3) and (4) of Table 4 report the corresponding estimation results. The coefficients on digital infrastructure are positive and significant at the 1% level, suggesting that digital infrastructure development is associated with improvements in the institutional environment of peripheral regions. Therefore, enhanced digital governance appears to strengthen institutional capacity in peripheral regions and facilitate collaborative innovation with core cities (B. Wang et al., 2022). These findings provide empirical support for Hypothesis 2.

Table 4. Mechanism analysis

	(1)	(2)	(3)	(4)
Variables	Market frictions		Institutional capacity	
D_{it}	0.081*	0.083**	0.051***	0.046***
	(0.042)	(0.043)	(0.015)	(0.015)
Constant	0.001	0.001	-0.001	-0.001
	(0.010)	(0.009)	(0.005)	(0.005)
Control	No	Yes	No	Yes
N	3224	3212	3224	3212
ML method	LassoCV	LassoCV	LassoCV	LassoCV
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

4.4 Heterogeneity analysis

4.4.1 Industry Type

Innovation activities vary across industries in terms of technological complexity and dependence on external knowledge and resources. As a result, the role of digital infrastructure in shaping collaborative innovation may differ by industry type. Following existing studies, we classify collaborative patents involving peripheral regions into emerging and non-emerging industries based on the official classification of strategic emerging industries released by the China National Intellectual Property Administration. Separate regressions are estimated for the two groups, Columns (1) and (2) of Table 5 report the results. The estimated effect of digital infrastructure is markedly stronger for collaborative innovation in emerging industries. This pattern is consistent with the nature of emerging sectors, which tend to rely more heavily on cross-regional knowledge flows and open forms of collaboration during the innovation process (Bathelt et al., 2004; Ascani et al., 2020). By reducing information transmission costs and improving the efficiency of long-distance coordination, digital infrastructure appears to facilitate deeper engagement of peripheral regions in intercity innovation networks, particularly in knowledge-intensive and rapidly evolving industries.

4.4.2 Collaboration mode

The impact of digital infrastructure on collaborative innovation in peripheral regions may also vary with the type of collaboration partner. We distinguish between three modes of collaboration: inter-firm collaboration, firm-institute collaboration, and inter-institute collaboration, and estimate separate regressions for each category. Columns (3) to (5) of Table 5 present the corresponding results. The estimated effect of digital infrastructure is strongest and statistically significant for inter-firm collaboration, while the coefficients for firm-institute and inter-institute collaboration are notably weaker and, in some specifications, negative. This pattern suggests that market-oriented actors are more responsive to the reductions in transaction and coordination costs enabled by digital infrastructure. Firms, driven by commercial

incentives, appear more willing to leverage digital connectivity to overcome spatial barriers and information asymmetries and to establish collaborative ties with enterprises located in core cities (Y. Wang et al., 2025). By contrast, collaborations involving research institutes or universities are often shaped by rigid administrative arrangements, funding rules, and academic evaluation systems, which may limit the extent to which digital infrastructure translates into expanded cross-regional collaboration (Rossoni et al., 2024). As a result, the role of digital infrastructure in facilitating intercity innovation networks appears more pronounced for firm-based collaborations than for those involving non-market actors.

Table 5. Heterogeneity analysis of industry type and Collaboration mode

	(1)	(2)	(3)	(4)	(5)
	Industry Type		Collaboration mode		
Variables	emerging	non-emerging	inter-firm	firm-ins	inter-ins
D_{it}	0.040**	0.022**	0.199***	0.010	-0.023**
	(0.020)	(0.010)	(0.067)	(0.009)	(0.011)
Constant	0.000	0.000	-0.004	-0.000)	0.000
	(0.004)	(0.003)	(0.016)	(0.002)	(0.002)
Control	Yes	Yes	Yes	Yes	Yes
N	3212	3212	3212	3212	3212
ML method	LassoCV	LassoCV	LassoCV	LassoCV	LassoCV
City FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes

4.5 Further analysis

4.5.1 Intellectual property protection

Intellectual property protection grants innovators legally enforceable exclusive rights over the outcomes of their inventive activities. In the absence of effective intellectual protection, innovation activities are more likely to be undermined by opportunistic behaviour, imitation, and unfair competition, weakening the alignment between innovation inputs and expected returns (Vivona et al., 2023). These concerns are particularly salient in cross-regional innovation collaboration, where the risks of free-riding and unintended knowledge leakage are higher and can directly affect the security and expected payoffs of technological spillovers. Peripheral regions that are able to offer credible Intellectual protection are therefore more likely to attract

innovation partners from core cities (Teece, 1986).

To examine whether intellectual protection conditions the effect of digital infrastructure on collaborative innovation, we introduce an interaction term between digital infrastructure and a measure of regional intellectual protection enforcement. Specifically, we use the establishment of specialized intellectual property courts as an indicator of IP protection and construct an interaction term $D_{it} \times M_{it}$, where D_{it} denotes the level of digital infrastructure and M_{it} is a dummy variable equal to one if a specialized intellectual protection court has been established in a given region and year. This specification allows us to assess whether the impact of digital infrastructure on intercity innovation collaboration varies with the strength of local intellectual protection. Columns (1) and (2) of Table 6 report the estimation results. The coefficient on the interaction term is positive and significant at the 1% level, indicating that stronger intellectual protection amplifies the positive effect of digital infrastructure on collaborative innovation involving peripheral regions. These results suggest that digital infrastructure is more effective when supported by credible legal protection, which mitigates collaboration risks.

4.5.2 Government R&D subsidies

Beyond legal institutions, government R&D subsidies represent another important policy instrument influencing the innovation capacity of peripheral regions. Innovation activities are characterized by substantial uncertainty, high upfront costs, and pronounced information asymmetries, which are particularly binding for firms located in peripheral regions with limited technological capabilities and weaker access to external finance (Cantner et al., 2019). Although collaborative innovation can help spread risks, firms must still commit significant resources over irregular and often lengthy R&D cycles. In this context, government R&D subsidies can mitigate market failures arising from positive knowledge externalities and strengthen firms' incentives to engage in innovative activities.

Consistent with the logic of intellectual property protection discussed above, we examine whether public R&D support enhances the role of digital infrastructure in facilitating intercity innovation collaboration. The results reported in Columns (3) and

(4) of Table 6 indicate that the positive effect of digital infrastructure on collaborative innovation involving peripheral regions is more pronounced when government R&D subsidies are available. The results suggest that R&D subsidies encourage innovation actors in peripheral regions to engage more actively in cross-regional collaboration, thereby allowing digital infrastructure to play a more effective role in supporting intercity collaborative innovation.

Table 6. Optimizing the path of digital infrastructure

	(1)	(2)	(3)	(4)
	Intellectual property protection		Government R&D subsidies	
Variables	Inncol	Inncol	Inncol	Inncol
$D_{it} \times M$	0.640***	0.659***	0.020***	0.020***
	0.192	(0.187)	(0.003)	(0.003)
Constant	-0.000	-0.000	0.000	0.001
	0.009	(0.009)	(0.009)	(0.009)
Control	No	Yes	No	Yes
N	3224	3212	3224	3211
ML method	LassoCV	LassoCV	LassoCV	LassoCV
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

5. Conclusion

This study examines whether digital infrastructure enables peripheral regions to overcome spatial constraints and become more deeply embedded in intercity innovation networks. Adopting a network perspective, our analysis moves beyond innovation outcomes measured at the city level and focuses instead on the collaborative ties linking peripheral and core cities. The findings show that digital infrastructure strengthens intercity innovation collaboration involving peripheral regions, improving their access to external knowledge and their position within national innovation networks. In this sense, the developmental significance of digital infrastructure lies not only in increasing innovation activity, but also in reshaping the relational structure of inter urban innovation systems.

The results also clarify how these effects are realized and why they vary across contexts. Digital infrastructure facilitates collaboration by reducing search, matching and coordination frictions, while its impact differs across collaboration modes,

industries and spatial settings. Stronger effects are observed in inter firm collaboration, in knowledge intensive emerging industries. Institutional conditions, including intellectual property protection and innovation subsidies, further strengthen these effects by enhancing peripheral regions' capacity to sustain cross regional collaboration and absorb external knowledge. These findings indicate that digital infrastructure functions as a relational enabler whose innovation benefits are shaped and reinforced by institutional arrangements and the spatial organization of innovation networks.

Several limitations should be noted. First, the design controls for an extensive set of observable city characteristics through the DML framework but cannot rule out selection on unobserved factors that may correlate with both pilot designation and collaborative innovation; we therefore interpret the estimates as conditional associations rather than as fully identified causal effects. Second, applicant-based patent records cannot distinguish between collaborative ties formed by incumbent firms in the peripheral city, ties sustained through inventor relocation, and ties formed by entrant firms newly attracted to the city. Untangling these mechanisms requires inventor-level disambiguated data that are not currently available for Chinese patents over the full sample period. Each of these limitations defines a direction for further research rather than a feature specific to the present study.

From a policy perspective, the findings suggest that digital infrastructure should not be treated as a stand alone instrument for reducing regional disparities. Its primary value lies in facilitating the integration of peripheral regions into existing intercity innovation networks rather than solely expanding local innovation capacity. Institutional policy tools such as intellectual property protection and innovation subsidies play a complementary role in this process by stabilising collaboration incentives and reducing uncertainty for external partners. This implies that digital infrastructure policies are likely to be most effective when coordinated with innovation policy instruments that shape firms' incentives to engage in cross regional collaboration. Rather than prioritising short term performance indicators, policy design should focus on fostering durable relational ties that allow peripheral regions

to participate more consistently in wider innovation networks. At the same time, the heterogeneous effects identified in the analysis point to the limits of uniform digitalization strategies. Policies aimed at promoting regionally balanced development therefore need to adopt a differentiated and place sensitive approach that aligns digital infrastructure investment with regional development paths and existing spatial networks. While the analysis is based on the Chinese context, the mechanisms identified are likely to be relevant for other countries where peripheral regions face persistent barriers to participation in intercity innovation systems.

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