Geopolitical Fragmentation and the Reorganization of Innovation Networks: Evidence from the Global 5G Industry

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Abstract

Frontier innovation depends on the international recombination of knowledge, but rising geopolitical tensions may disrupt these connections. We examine how geopolitical fragmentation reshapes firms' innovation networks and innovation quality using 96,437 priority patent filings and 47,823 firm–article observations for the world's leading 5G firms between 2010 and 2023. Our shift–share design combines firms' pre-period exposure to cross-bloc inventor integration with the subsequent global decline in such co-invention.

Greater exposure to fragmentation shocks reduces inventor collaboration across geopolitical blocs. A one-standard-deviation increase in firms' exposure to the fragmentation shock lowers the probability of conflict-bridge inventor collaboration by 2.3 pp, about one-quarter of its mean, with the broadest adjustment among Chinese firms. More exposed Chinese firms also exhibit a higher probability of producing breakthrough patents and greater citation impact. Their scientific collaboration networks become more domestically oriented: the domestic share of university partners rises by 7.8 pp, whereas the rival-bloc share falls by 4.5 pp.

These findings suggest that geopolitical fragmentation can reconfigure innovation networks rather than simply contracting them. Among Chinese firms, this reorganization occurs without a decline in innovation quality. More broadly, the consequences of geopolitical fragmentation depend on how firms reorganize their knowledge networks as opportunities for cross-bloc knowledge integration decline.

Keywords: Geopolitical fragmentation, Technological decoupling, 5G, Innovation networks, Cross-border collaboration, Innovation performance

JEL codes: F23, O32, O33, L96, D85

1. Introduction

China's transformation from a technology importer to a major innovation actor is one of the defining developments in the world economy of the past two decades (Fu, 2015; Lewin et al., 2016). Although China's technological catch-up has been uneven across industries, recent evidence indicates that it has reached or approached the global technological frontier in key sectors such as electronics and electrical equipment (Zhu & Li, 2025). Chinese firms now operate at or near the technological frontier in a growing range of strategically important technologies such as batteries, electric vehicles, artificial intelligence, and telecommunications infrastructure (Zhang, 2024; Koski & Rouvinen, 2025). This transformation raises an important question about the resilience of China's innovation system. How does rising geopolitical friction reshape firms' knowledge networks, and with what consequences for innovation at the technological frontier?

This question has become increasingly important as strategic competition between the United States and China has expanded into advanced technologies such as 5G. Export controls, entity-list sanctions, and other technology restrictions have been widely discussed as instruments for reshaping trade patterns, global value chains, and access to advanced technologies (Nocetti, 2022). Yet international knowledge diffusion is also a fundamental driver of technological development (Lind & Ramondo, 2024), suggesting that restrictions on cross-border interaction may also affect innovation rather than merely trade and production. Because innovation depends on combining knowledge across firms, countries, and inventor teams, geopolitical fragmentation may reshape not only the intensity but also the organization of knowledge creation.

This study examines how rising geopolitical tensions reshape cross-border knowledge production in frontier 5G technologies. We study three dimensions of this adjustment: whether geopolitical fragmentation changes the structure and composition of cross-bloc inventor networks, whether these changes are accompanied by shifts in innovation outcomes, and whether affected firms reorganize their scientific collaboration networks. Our empirical analysis combines patent data on 96,437 priority filings by the leading 5G patenting firms with publication data covering 47,823 firm-article observations. This allows us to trace how the same geopolitical shocks propagate across technological inventions and scientific collaborations.

We study these questions in the context of fifth-generation mobile communication (5G) infrastructure technologies, a strategically important domain at the center of the U.S.–China technological rivalry. Beginning in 2018, escalating trade and technology tensions led to a series of U.S. export controls and entity-list sanctions targeting firms such as Huawei. Concerns over technological dependence and network security also prompted the European Union to introduce the EU 5G Toolbox, a coordinated framework for managing risks associated with high-risk vendors. Together, these developments have increased the costs of cross-border

collaboration and substantially altered the incentives for organizing inventive activities across geopolitical boundaries.

Our conceptual framework builds on the literature on multinational innovation and global R&D networks. Prior research shows that firms benefit from accessing geographically dispersed knowledge and that multinational enterprises organize such recombination through international R&D networks (Almeida & Kogut, 1999; Kogut & Zander, 1993; Mudambi, 2008). It also shows that the benefits of diversity are non-linear, as broader knowledge access must be balanced against coordination and integration costs (Reagans & Zuckerman, 2001; Seo et al., 2020). We extend this literature by arguing that geopolitical fragmentation introduces an institutional source of integration friction distinct from technological or geographic distance. Rather than simply reducing innovation, geopolitical fragmentation shifts the balance between the benefits of cross-border knowledge recombination and the costs of coordinating geographically and institutionally distant collaborations. Therefore, firms may respond by reorganizing the geographic and institutional structures of their knowledge networks rather than simply reducing their innovative efforts.

Examining both patents and scientific publications allows us to capture distinct but complementary dimensions of firms' knowledge networks. Patents trace the geographic organization of appropriable inventions associated with the firm: inventor locations reveal where technological knowledge is developed, while cross-bloc co-invention captures collaboration across geopolitical boundaries. Scientific publications capture a more open form of knowledge production, often involving collaboration with universities and other research institutions. Author affiliations reveal with whom firms engage in scientific knowledge creation. The distinction is not simply between applied and basic research but between different modes of knowledge production that vary in appropriability, disclosure, and the identity of collaborating partners. Studying both margins allows us to examine whether geopolitical fragmentation reshapes inventive and scientific collaboration networks in similar or different ways.

We focus on core 5G infrastructure technologies and analyze cross-border inventive collaborations involving leading patenting firms in this domain. Innovation in 5G is highly concentrated: during 2010–2023, the top 50 patent owners accounted for approximately 70% of all patents in core 5G technologies. Our empirical analysis covers 47 of these firms (excluding three research institutes) and 96,437 priority patent applications. Because these firms are headquartered across the principal geopolitical blocs involved in the current technological rivalry, our design moves beyond a simple China-versus-West comparison and allows us to explore how changes in knowledge networks vary across firms embedded in different innovation systems as geopolitical friction increases.

We find that rising geopolitical fragmentation significantly reduces cross-bloc inventive collaboration in core 5G technologies, but the adjustment differs markedly across geopolitical blocs. A one-standard-deviation increase in firms' exposure to the fragmentation shock lowers

the probability of conflict-bridge inventor collaboration by approximately 2.3 pp, relative to a sample mean of roughly 9 percent. Chinese firms exhibit the most comprehensive adjustment, with significant reductions in cross-bloc inventor bridges, inventor-bloc diversity, and participation by rival-bloc inventors. Firms from other Asian economies display a similar pattern, whereas European firms primarily reduce rival bloc participation without a corresponding decline in overall inventor diversity. U.S. firms show little systematic adjustments.

Despite this contraction in cross-bloc collaboration, Chinese firms do not experience weaker innovation outcomes. Chinese firms with greater exposure to the fragmentation shock have a higher probability of producing breakthrough patents and patents with greater citation impact, whereas more exposed European firms experience declining citation-based patent quality, and U.S. firms show little systematic change. Applying the same shift–share design to publication data reveals an accompanying reorientation of firms' scientific collaboration networks. Chinese firms that are more exposed to foreign competition are 13.5 pp more likely to collaborate with universities and 16.1 pp more likely to have a domestic university partner; their domestic share of university partners rises by 7.8 pp, while the rival bloc's share falls by 4.5 pp. The probability of collaborating with any rival-bloc university is unaffected, indicating that this reweighting reduces the relative importance of Western partners rather than eliminating Western engagement. More exposed Chinese firms therefore do not exit Western academic networks, but these networks account for a smaller share of a collaboration portfolio that becomes increasingly domestically oriented. Together, these findings point to a reorganization, rather than a simple contraction, of Chinese firms' knowledge networks in response to geopolitical fragmentation.

This paper makes three contributions. First, it conceptualizes geopolitical fragmentation as an institutional source of integration friction in global innovation networks, which is distinct from the technological and geographic frictions emphasized in previous research. Empirically, we show that this friction reshapes cross-border inventor networks asymmetrically across geopolitical blocs rather than imposing a uniform cost on international collaboration. Second, this study contributes to research on China's innovation system by documenting how geopolitical fragmentation is associated with a reorganization of Chinese frontier firms' scientific collaboration networks, with greater engagement with domestic university partners and a declining relative weight of rival bloc partners. Third, it contributes to the literature on technological upgrading and innovation under geopolitical fragmentation by showing that declining cross-bloc collaboration does not necessarily coincide with weaker innovation outcomes. By observing both appropriable inventions and scientific collaboration for the same firms, we show that geopolitical fragmentation is associated with distinct but related forms of reorganization across these two dimensions of knowledge production. Overall, our findings highlight the potential importance of domestic scientific and technological capabilities in shaping how firms adjust their knowledge networks as geopolitical frictions increase.

The remainder of the paper is organized as follows. Section 2 develops the conceptual framework. Section 3 describes the patent and publication data and the measures constructed from them. Section 4 presents the empirical strategy. Section 5 reports the results for cross-bloc inventive collaboration, innovation outcomes and scientific collaboration networks. Section 6 concludes and discusses the implications for innovation management and technology policy.

2. Conceptual framework

Innovation often depends on combining knowledge from diverse sources. Because knowledge spillovers are geographically localized (Jaffe et al., 1993; Audretsch & Feldman, 1996), firms benefit from accessing distinct and locally embedded knowledge pools across locations (Almeida & Kogut, 1999). A central rationale for multi-location R&D is therefore to tap into heterogeneous scientific and technological capabilities located in different regions (Chung & Alcácer, 2002; Alcácer & Zhao, 2012). By distributing research activities across locations, firms expand their opportunities for recombinant search and access a broader range of scientific and technological knowledge.

However, accessing dispersed knowledge requires integration. Multinational enterprises organize this process through internal and external knowledge networks (Kogut & Zander, 1993; Gupta & Govindarajan, 2000; Ernst & Kim, 2002; Mudambi, 2008). Cross-border inventor mobility, repeated interactions, and local embeddedness help build the trust and shared understanding needed to effectively recombine geographically dispersed knowledge (Castellani et al., 2022; Bathelt & Li, 2020). These benefits must be balanced against the coordination and integration costs associated with geographic and technological diversity. Prior research has therefore found non-linear returns to diversity, with broader knowledge access improving innovation only up to the point at which integration costs become too large (Reagans & Zuckerman, 2001; Seo et al., 2020; Vestal & Danneels, 2022). Firms with stronger internal capabilities can better manage these costs and absorb geographically dispersed knowledge (Moreira et al., 2018; Belderbos et al., 2023).

We extend this framework by introducing geopolitical fragmentation as an additional, conceptually distinct source of friction in knowledge recombination. Existing research distinguishes continuous spatial heterogeneity from the discrete discontinuities associated with national borders (Beugelsdijk & Mudambi, 2013; Scalera et al., 2018). We argue that geopolitical fragmentation adds an institutional dimension to these border effects by introducing policy-induced frictions in knowledge exchange across geopolitical boundaries that are distinct from the underlying geographic and technological distances between inventors. Export controls, entity list sanctions, and technology transfer restrictions can increase the costs and uncertainty associated with cross-bloc collaboration. Such frictions may also weaken firms' incentives to engage in cross-bloc research when they reduce the

expected private returns to knowledge creation, consistent with prior research on appropriation and R&D incentives (Arora et al., 2021). Therefore, geopolitical fragmentation reduces the relative attractiveness of cross-bloc knowledge recombination and may shift innovative activity toward domestic or within-bloc collaboration. Data governance fragmentation and supply chain security concerns may reinforce this shift by pushing multinational firms toward parallel, region-specific innovation strategies, even at the cost of duplicated investment (George & Schillebeeckx, 2022).

The consequences of innovation depend, in part, on whether firms can reorganize their knowledge networks. Recombinant search research suggests that moderately distant knowledge can enhance innovation, whereas excessive distance and complexity can reduce its benefits (Fleming & Sorenson, 2004; Uzzi et al., 2013; Kaplan & Vakili, 2015; Choudhury & Haas, 2018). Moreover, because much useful knowledge is new to the firm rather than unique to the world, comparable knowledge may often be available from alternative sources (Xiao et al., 2022). Therefore, firms facing greater geopolitical friction may substitute domestic or within-bloc partners for cross-bloc collaborators, particularly when locally available partners provide knowledge sufficient for the task at hand (Fitjar & Gjelsvik, 2018). Geopolitical fragmentation thus changes the trade-off between access to complementary knowledge and the costs of integration: as cross-bloc collaboration becomes more costly, firms have stronger incentives to reorganize inventive and scientific collaboration toward domestic or within-bloc sources.

The ability to make such substitutions depends on the knowledge resources available to the firm. This argument is connected to research on absorptive capacity, or the ability to identify, assimilate, and exploit external knowledge (Cohen & Levinthal, 1990). Domestic R&D can strengthen this capacity and reduce dependence on specific foreign knowledge sources. Belderbos et al. (2015) show that the relationship between domestic and foreign R&D varies with technological position: in technologically lagging industries, domestic R&D helps firms absorb foreign knowledge, whereas at the technological frontier, it can increasingly provide an alternative source of technological capabilities. Firms embedded in stronger domestic knowledge systems should therefore be better positioned to replace cross-bloc knowledge with domestic or within-bloc alternatives. By contrast, firms with weaker domestic capabilities may remain more dependent on cross-bloc knowledge and more vulnerable to disruptions in international collaboration.

Taken together, these arguments imply that geopolitical fragmentation may reshape both the organization of knowledge production and its innovation outcomes. Firms with greater prior dependence on cross-bloc knowledge networks should adjust more strongly as geopolitical frictions increase. Cross-bloc inventor collaboration and the geopolitical diversity of inventive teams should decline as firms shift their activities toward domestic or within-bloc partners. Scientific collaboration networks may undergo similar geographic reorientations when suitable domestic partners are available. The implications for innovation quality, however, are

theoretically ambiguous: losing access to complementary cross-bloc knowledge may reduce innovation performance, while successful substitution toward alternative knowledge sources may offset these losses.

3. Data and measurement

3.1 Data sources

Our empirical analysis focuses on the leading patenting firms in core 5G technologies, identified from the LexisNexis (2025) ranking of 5G patent holders and standards contributors based on the ETSI data. Starting with the top 50 organizations in this ranking, we excluded three research institutes and retained 47 companies for the empirical analysis.

Patent data were retrieved from the PatentInspiration database. We organize the data at the patent-family level and retain one observation per family, corresponding to the earliest priority application filed between 2010 and 2023. This approach avoids double counting across jurisdictions and anchors each invention to its original filing date.

We identify core 5G patents using the USPTO (2022) classification and four Cooperative Patent Classification (CPC) subclasses: H04W72, H04L5, H04L1, and H04B7. These technology domains account for a large share of ETSI-declared 5G patent filings and capture the key aspects of radio resource management, transmission, and communication system performance. Restricting the sample to patents containing at least one of these CPC subclasses yields 96,437 unique priority patent applications filed between 2010 and 2023.

We group firms and inventors into four geopolitical blocs based on the country of headquarters or inventor location: China, the United States, the European Union and United Kingdom (EU/UK), and other Asian economies. These groupings are used throughout the analysis to distinguish between domestic, within-bloc, and cross-bloc collaborations. Patenting activity is distributed across all four blocs: 31.1% of patents are assigned to firms headquartered in other Asian economies, 28.4% to Chinese firms, 28.0% to U.S. firms, and 12.5% to firms headquartered in the EU/UK.

To complement the patent analysis, we constructed a dataset of scientific publications using OpenAlex for the same firms and period. The publication sample is described in greater detail in Section 3.3 and allows us to examine the institutional and geographic structures of firms' scientific collaboration networks.

3.2 Patent-based measures of inventive collaboration and innovation

Consistent with the conceptual framework developed in Section 2, our empirical analysis focuses on collaboration at the inventor level as a measure of cross-border knowledge recombination. Inventor locations allow us to observe where inventive activity takes place,

even when the resulting patent is owned by a single firm. This distinction is important because international inventive collaboration need not involve joint patent ownerships.

Figure 1 shows the share of patents involving at least one inventor located outside the headquarters bloc of the focal firm. Cross-bloc inventor collaboration remains substantial throughout the sample period. Patents assigned to U.S., European, and Chinese firms frequently include inventors located in other geopolitical blocs, with the share of such patents typically ranging between 10 and 30 percent. Although the prevalence of cross-bloc collaboration varies over time, multinational inventor teams remain a common feature of inventive activity in core 5G technologies.

Figure 1. Cross-Bloc Inventor Integration in Core 5G Technologies

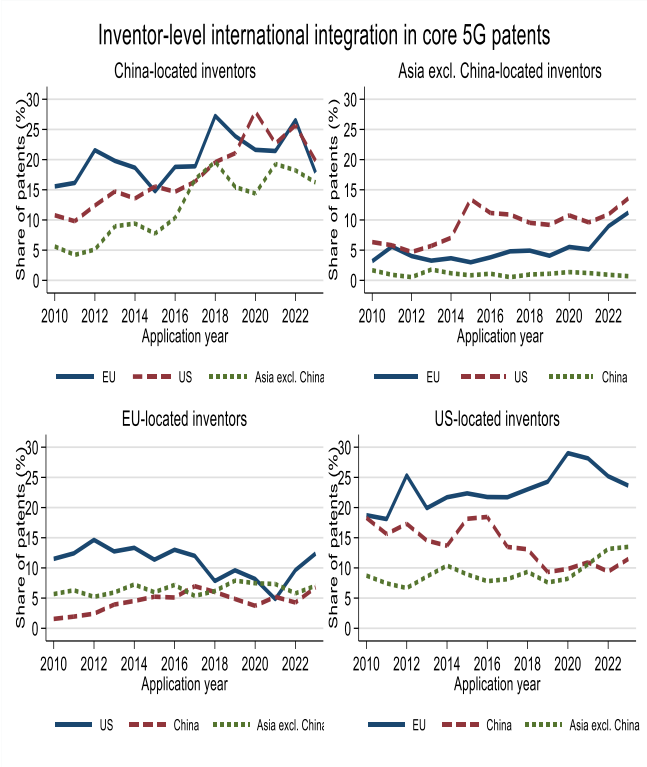
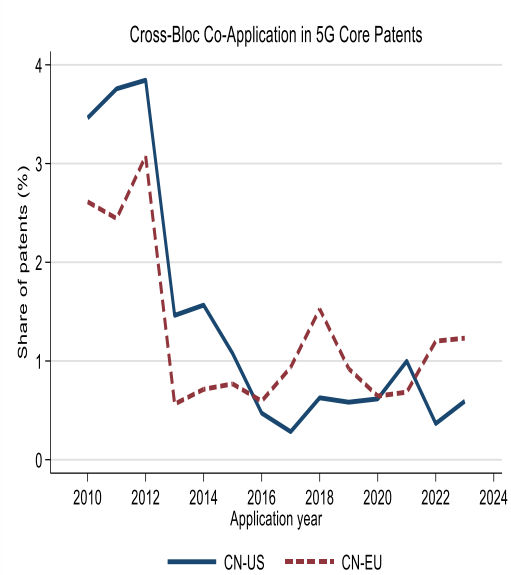


Figure 2 provides a complementary view of international inventive collaboration by reporting the annual share of patents jointly owned by Chinese and Western firms. Such China–West co-application is rare throughout the sample period, accounting for less than two percent of annual patent applications in most years. Therefore, joint ownership captures only a small fraction of cross-border inventive activity visible through inventor locations.

Taken together, Figures 1 and 2 illustrate why we focus on inventor-level collaboration in our empirical analysis. Cross-border inventor integration is a common feature of inventive activity in core 5G technologies, whereas formal joint patent ownership between Chinese and Western firms is rare.

Figure 2. Cross-Bloc Co-Application in Core 5G Technologies



We constructed several patent-level measures to capture the structure and composition of inventor networks. The three bridge indicators identify patents involving inventors located on different sides of geopolitical boundaries. The U.S.–China and EU–China bridge indicators equal one when a patent includes inventors located in both blocs. The conflict-bridge indicator takes the value of one when a patent includes inventors located on both sides of the China–West geopolitical divide. We further measure the share of inventors located in rival geopolitical blocs and inventor-bloc diversity, calculated as one minus the Herfindahl–Hirschman index across the inventor blocs. Whereas bridge variables capture the presence of particular cross-bloc links, the latter characterizes the broader geopolitical composition of inventive teams.

Innovation outcomes are measured using two complementary indicators of patent quality: the breakthrough-patent indicator equals one when a patent falls within the top 5% of the forward-citation distribution within its application year and core 5G CPC subclass. To ensure meaningful within-cell rankings, this measure is constructed only for application-year × CPC-subclass cells that contain at least 30 patents. The second measure, the normalized log forward citations, captures the citation impact relative to patents filed in the same application year and technology class. All specifications account for the four core 5G CPC subclasses to capture the technological heterogeneity within the sample.

Table 1 reports the descriptive statistics for the patent-based variables used in the empirical analysis.

Table 1. Descriptive statistics

	N	mean	sd	min	max
Conflict bridge	96437	0.095	0.293	0.000	1.000
US-CN bridge	96437	0.089	0.284	0.000	1.000
EU-CN bridge	96437	0.027	0.161	0.000	1.000
Conflict-bloc inventor share	96437	0.098	0.252	0.000	1.000
Inventor bloc diversity (1-HHI	96358	0.090	0.179	0.000	0.800
Normalized log forward citations	96437	0.426	0.611	0.000	6.081
Breakthrough: top5%	96437	0.049	0.216	0.000	1.000
CPC: H04W72	96437	0.667	0.471	0.000	1.000
CPC: H04L5	96437	0.536	0.499	0.000	1.000
CPC: H04L1	96437	0.339	0.473	0.000	1.000
CPC: H04B7	96437	0.220	0.414	0.000	1.000

Note: The US–CN and EU–CN bridge variables are binary indicators equal to one if a patent includes inventors located in both blocs. A conflict bridge is a binary indicator equal to one if a patent includes inventors located on both sides of the China–West geopolitical divide. Conflict-bloc inventor share measures the share of inventors in rival geopolitical blocs. Inventor bloc diversity is measured as 1-HHI across the inventor blocs. CPC indicators identify the main core 5G technology classes and are not mutually exclusive. Breakthrough patents are a binary indicator equal to one if a patent belongs to the top 5% of the forward-citation distribution within its application year and core 5G CPC subclass.[1] Relative citation impact is measured as the logarithm of forward citations normalized by the average citation count of patents filed in the same application year and core 5G CPC subclass.

3.3 Scientific publication data and collaboration measures

Publication data were constructed from OpenAlex. For each of the 47 sample firms, we retrieved articles published between 2010 and 2023 that included at least one author affiliated with the focal firm in its headquarters country and retained all institutional affiliations appearing in each qualifying article. Forty of the 47 firms have a resolvable OpenAlex institutional identifier. Restricting the sample to Engineering and Computer Science and firms with a sufficiently dense publication record to measure pre-period exposure yields 47,823 firm–article observations for 33 firms.

Publication data allow us to observe the institutional dimension of firms' knowledge networks that cannot be recovered from inventor addresses alone. Collaboration partners are defined as external institutions other than the units of the focal firm and are classified using the institution types provided by OpenAlex. University partners are external institutions classified as educational institutions. Each partner is assigned to a geopolitical bloc using its recorded country, applying the same bloc classification as in the patent analysis.

We distinguish between the existence and composition of university collaborations. The first set of measures identifies whether an article includes any external university partner, any domestic university partner, or any rival-bloc university partner. Domestic partners are located in the focal firm's headquarters country. For European and U.S. firms, the rival bloc is China; for

[1] To ensure meaningful within-cell citation rankings, the breakthrough measure is constructed only for application-year × CPC-subclass cells containing at least 30 patents.

Chinese and other Asian firms, it is the West. The second set of measures captures the geographic composition of collaboration through the domestic and rival-bloc shares of university partners, conditional on the article having at least one university partner. Reading the existence and composition margins together allows us to distinguish the loss of a relationship from a change in its relative importance within the firm's broader collaboration portfolio.

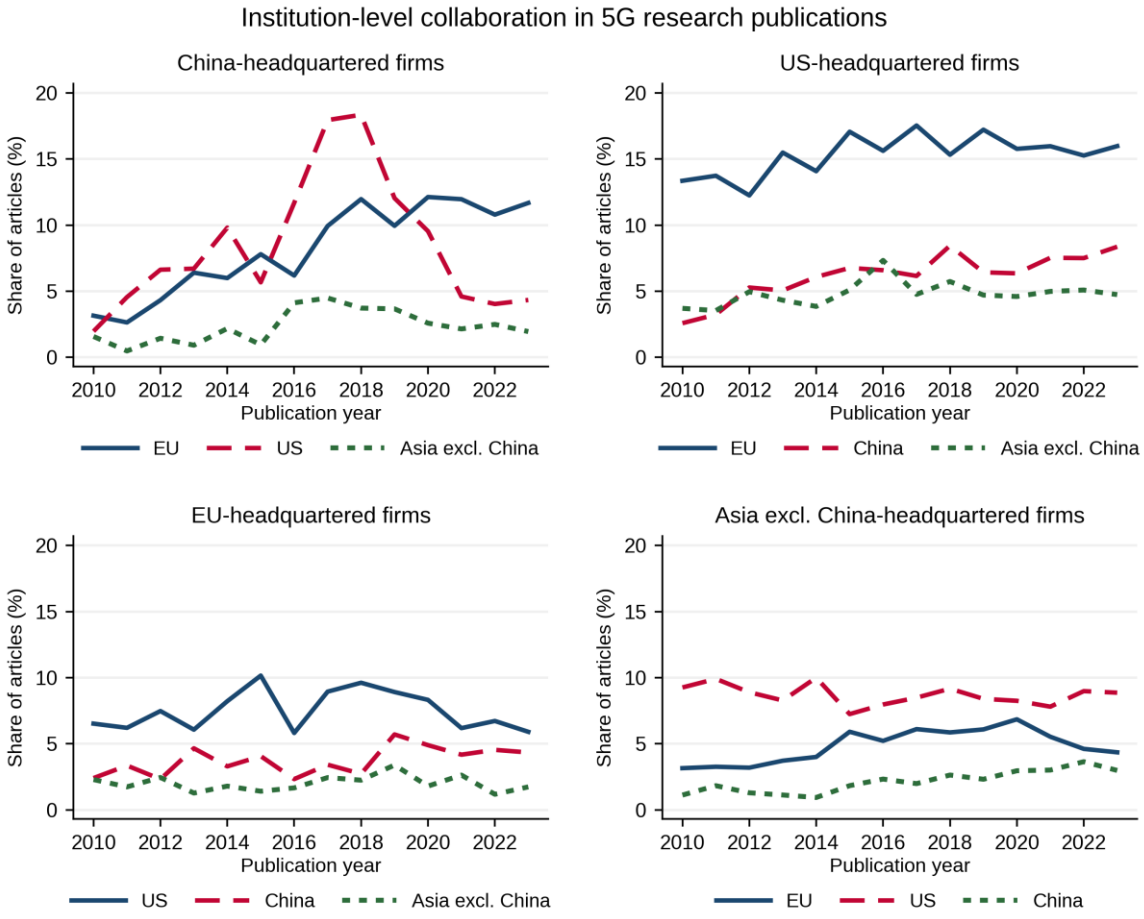
Two measurement limitations should be noted. OpenAlex truncates author lists at 100 entries, affecting 60 articles that were excluded from the sample. In addition, institutional coverage is less complete for corporate than for academic affiliations; therefore, external partner counts should be interpreted as lower bounds.

Table 2. Publication sample and descriptive statistics

	Firms	Firm-article observations	Any university partner (%)	Any domestic partner (%)	Any rival-bloc partner (%)
Panel A. Sample composition by headquarters bloc					
China	5	6,625	74.1	63.9	15.8
United States	8	12,840	76.3	52.8	6.1
EU/UK	9	9,307	74.1	48.9	3.7
Asia excl. China	11	19,051	69.8	59.1	12.8
All firms	33	47,823	73.0	56.1	9.6
Panel B. Collaboration measures	*Mean*	*SD*	*Min*	*Max*	*Observations*
University partners per article	1.25	1.41	0	51	47,823
University partners per article, if any	1.71	1.39	1	51	34,897
Domestic share of university partners (%)	68.4	42.1	0	100	34,897
Rival-bloc share of university partners (%)	8.9	25.1	0	100	34,897
Authors per article	5.14	4.06	0	100	47,823
Domestic share of authors (%)	83.5	27.7	0	100	47,400

Table 2 reports the descriptive statistics for the publication sample. Seventy-three percent of the firm–article observations include at least one external university partner. Among articles with a university partner, the average article has 1.71 such partners, and collaboration is predominantly domestic: 68.4% of university partners are located in the focal firm's headquarters country, compared with 8.9% in the rival bloc. The prevalence of rival bloc university collaboration also varies substantially across headquarters blocs.

Figure 3. University Collaboration across Geopolitical Blocs, by Headquarters Bloc



Notes: Each panel plots the share of articles of firms headquartered in one bloc carrying at least one external university partner located in each of the other three blocs.

Figure 3 shows the geographic distribution of firms' university collaborations across geopolitical blocs. Each panel reports the share of articles involving at least one university partner located in each of the other three blocs for firms headquartered in one bloc. The most pronounced change occurs among Chinese firms: collaboration with U.S. universities rises through 2018 and then declines sharply, while collaboration with European universities increases over the same period. Collaboration with universities elsewhere in Asia remains

limited. The corresponding patterns for U.S., European, and other Asian firms are comparatively stable over time.

Figure 4. Collaboration with Domestic Universities, by Headquarters Bloc

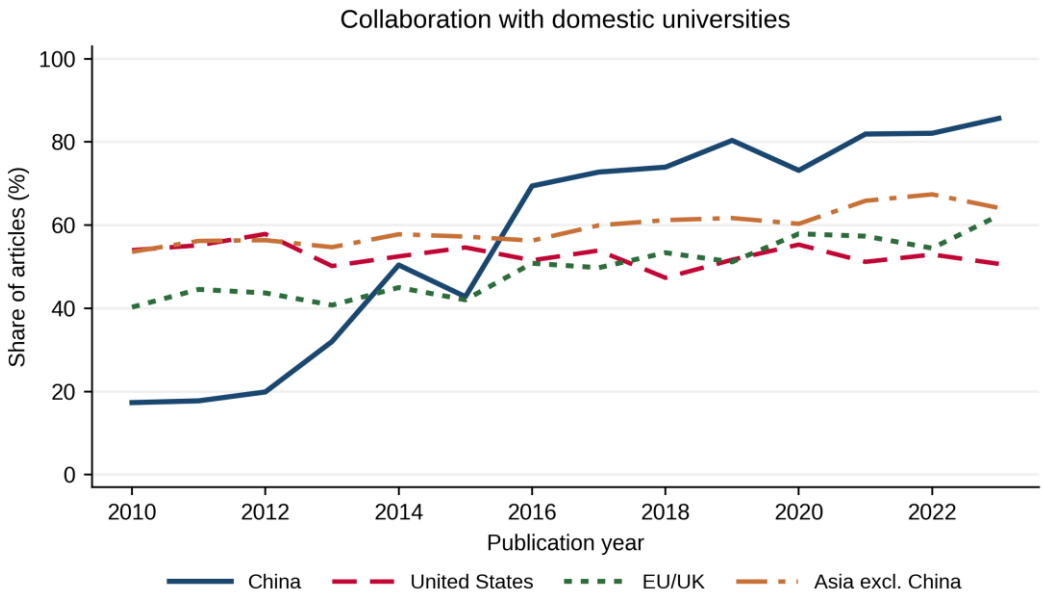


Figure 4 complements this view by showing collaborations with universities located in the focal firm's headquarters country. Domestic university collaboration is relatively stable for U.S. firms and increases gradually among European and other Asian firms. Chinese firms display a markedly different pattern: the share of articles involving a domestic university partner rises from about 17 percent in 2010 to 86 percent in 2023.

4. Empirical strategy

We estimate the effects of geopolitical fragmentation using a continuous shift–share exposure design, which we apply to two sets of outcomes: patent-level measures of cross-bloc inventive collaboration and innovation performance, as defined in Section 3.2, and article-level measures of scientific collaboration, as defined in Section 3.3. We classify inventor and partner institution locations into four geopolitical blocs: the United States, the European Union and the United Kingdom, China, and other Asia. Cross-bloc collaboration refers to patents involving inventors located in both Western economies (the U.S. or EU/UK) and China. Identification comes from cross-sectional differences in firms' pre-period exposure to headquarters-specific cross-bloc inventor mixing in 5G and time-series variations in the global decline of cross-bloc co-invention.

Specifically, we construct firm-level exposure measures based on pre-period collaboration patterns from 2010 to 2011. Our baseline exposure measure is headquarters-specific and captures firms' pre-period reliance on cross-bloc inventor integration between Western economies and China. For firms headquartered in the EU/UK and the United States, exposure is measured using EU–China and U.S.–China inventor mixing, respectively. For firms headquartered in China and other Asian economies, exposure is measured using West–China inventor mixing, where the Western bloc comprises inventors located in the United States and the EU/UK. Inventor mixing is defined as the product of inventor shares across the respective blocs and therefore increases when inventors from both blocs contribute more intensively to the same patents. Because the exposure measure is defined prior to the escalation of geopolitical tensions, it is predetermined with respect to subsequent fragmentation dynamics.

To capture the time variation in geopolitical fragmentation, we construct annual shocks based on changes in cross-bloc co-invention intensity outside the focal firm sample. Specifically, we use first-priority patent families from the Patent Inspiration database and compute annual cross-bloc co-invention shares after excluding all firms in the estimation sample. Shocks are defined relative to patenting activity in the relevant geopolitical bloc and are matched to firms based on their headquarters location. For firms headquartered in the EU/UK and the United States, the shocks capture changes in EU–China and U.S.–China co-invention intensity. For firms headquartered in China and other Asian economies, the shocks capture changes in China–West co-invention intensity as measured from the Chinese side of the collaboration network. Therefore, the resulting shocks reflect changes in the broader cross-bloc co-invention environment without incorporating the patenting activity of focal firms. Before constructing the Bartik exposure, the annual changes in cross-bloc co-invention intensity were multiplied by −1 so that higher values corresponded to stronger geopolitical fragmentation and then standardized to have a mean of zero and unit variance.

Our baseline reduced-form specification is

$$Y_{ipt} = \beta(Exposure_i \times Shock_t) + \mu_i + \lambda_t + \varepsilon_{ipt} \qquad (1)$$

where Y_{ipt} denotes an outcome for firm (i) in year (t). In patent analysis, outcomes are measured at the patent level and capture cross-bloc inventor integration or innovation quality. In the publication analysis, outcomes are measured at the firm–article level and capture the existence and geographic composition of university collaborations.

Conflict-bridge collaboration captures the existence of inventor links spanning the China–West geopolitical divide, and inventor bloc diversity captures the extent to which inventive activity is distributed across geopolitical blocs. The baseline analysis additionally examines U.S.–China and EU–China inventor bridges, which decompose cross-bloc collaboration into its two principal bilateral channels, as well as the conflict-bloc inventor share, which captures the intensive-margin composition of inventor teams. Inventor-bloc diversity is measured as $1 -$

HHI, where the Herfindahl–Hirschman Index is calculated using inventor shares across the five geopolitical blocs (United States, EU/UK, China, Asia excluding China, and the rest of the world). Higher values indicate more geographically diversified inventor teams.

Innovation outcomes are measured using normalized log forward citations and a breakthrough patent indicator. Relative citation impact captures the technological influence of a patent relative to others filed in the same application year and technology class, while the breakthrough indicator identifies patents in the top five percent of the forward-citation distribution within their application year and core 5G CPC subclass.

Firm fixed effects (μ_i) absorb time-invariant differences in firms' technological portfolios, baseline international orientation, and collaboration strategies, while application-year fixed effects (λ_t) control for aggregate shocks common to all firms (e.g., technology-specific developments). The standard errors are clustered at the firm level.

Identification follows the logic of shift–share designs: the geopolitical shock varies over time and is assigned according to firms' headquarters location, while exposure varies across firms and is fixed in the pre-period. Therefore, coefficient β is identified from differential within-firm adjustments that are proportional to firms' prior dependence on cross-bloc knowledge recombination. Intuitively, when cross-bloc co-invention declines globally, firms that previously relied more heavily on EU–China, U.S.–China, or broader China–West inventor integration should experience larger adjustments in the geographic composition of their teams. The key identifying assumption is that, in the absence of geopolitical fragmentation, firms with different levels of pre-period exposure would not exhibit systematically different trends in the relevant outcomes.

Several features of the empirical setting strengthen this assumption. First, exposure is measured clearly before the observed decline in cross-bloc co-invention intensity, limiting concerns about anticipatory adjustment. Second, the patent analysis is confined to core 5G technologies, mitigating concerns regarding cross-industry compositional shifts. Third, firm fixed effects ensure that identification relies on within-firm adjustments rather than cross-sectional differences in the level of internationalization. Year fixed effects absorb common macroeconomic, technological and regulatory shocks.

Importantly, geopolitical fragmentation is not modeled as a discrete policy break but as a continuous change in cross-bloc integration intensity. Therefore, the estimated coefficients capture reduced-form responses to increasing geopolitical friction across inventive collaboration, innovation outcomes, and scientific collaboration. These should be interpreted as reflecting the combined consequences of export controls, regulatory tightening, and strategic decoupling, which altered the conditions for cross-bloc knowledge recombination.

We complement the baseline estimates with a dynamic shift–share specification that interacts the standardized shift–share measure with the application-year indicators. The resulting estimates trace the evolution of the effects of fragmentation exposure on conflict-bridge

collaboration and inventor-bloc diversity over time. Because fragmentation shocks evolve continuously rather than at a discrete treatment date, we use 2018 only for normalization and do not interpret it as the onset of treatment.

For the publication outcomes, we carry over the same firm-level exposure measure and annual fragmentation shift used in patent analysis. Equation (1) is estimated over firm–article observations, with publication-year in place of application-year fixed effects, and standard errors clustered at the firm level. The outcomes are the university collaboration measures defined in Section 3.3.

5. Estimation results

5.1 Cross-bloc collaboration

We begin by examining whether geopolitical fragmentation reduces cross-bloc inventive collaboration across the full sample of frontier 5G firms. This provides a benchmark against which we subsequently assess whether Chinese firms respond differently from firms headquartered in other geopolitical blocs. Table 3 reports the baseline reduced-form estimates of the relationship between geopolitical fragmentation and cross-bloc collaborations. The coefficient of interest captures the interaction between firms' pre-existing exposure to cross-bloc inventor integration and the annual variation in global cross-bloc co-invention. In a shift–share (Bartik) interpretation, the estimates measure how firms with different levels of pre-period cross-bloc integration adjust their inventor networks as the global co-invention environment becomes more fragmented.

Table 3. Baseline effects of geopolitical fragmentation on cross-bloc innovation collaboration

	(1) Conflict bridge	(2) US-CN bridge	(3) EU-CN bridge	(4) Conflict-bloc inventor share	(5) Diversity
Modified exposure × fragmentation shock (std)	-0.023***	-0.018**	-0.005	-0.009*	-0.016***
	(0.007)	(0.007)	(0.003)	(0.005)	(0.005)
Constant	0.105***	0.089***	0.027***	0.098***	0.090***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Observations	96437	96437	96437	96437	96358
R-squared	0.111	0.130	0.067	0.128	0.139

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The results indicate a systematic decline in cross-bloc inventor integration among firms that were more exposed to such collaboration before the intensification of geopolitical fragmentation. A one-standard-deviation increase in the exposure–shock interaction is associated with a 2.3 pp decline in the probability of conflict bridge collaboration and a 1.8 pp decline in the probability of a U.S.–China inventor bridge. These effects are economically meaningful, given that the average probabilities of conflict-bridge and U.S.–China bridge collaboration are approximately 9 and 8 percent, respectively. In contrast, the estimated effect on EU–China inventor bridges is small and statistically insignificant.

The results further suggest that geopolitical fragmentation affects the broader composition of inventor teams. Firms with greater pre-period exposure experienced a decline in the share of inventors located in rival geopolitical blocs and a reduction in inventor-bloc diversity. Because inventor diversity captures the distribution of inventors across the five geopolitical blocs, a negative coefficient indicates a decline in the geographic heterogeneity of inventive teams. Taken together, these findings suggest that geopolitical fragmentation reduces not only the incidence of cross-bloc inventor collaboration but also the diversity of inventor networks within frontier 5G innovation.

Table 4. Bloc-specific heterogeneity in responses to geopolitical fragmentation

	(1) Conflict bridge	(2) Conflict-bloc inventor share	(3) Diversity
China: Modified exposure × fragmentation shock (std)	-0.019***	-0.011**	-0.015***
	(0.007)	(0.005)	(0.005)
EU: Modified exposure × fragmentation shock (std)	-0.208*	-0.494***	-0.046
	(0.106)	(0.121)	(0.134)
US: Modified exposure × fragmentation shock (std)	0.028	-0.005	0.016
	(0.022)	(0.018)	(0.029)
Asia (excl-CN): Modified exposure × fragmentation shock (std)	-0.026***	-0.032***	-0.022*
	(0.007)	(0.009)	(0.012)
Constant	0.086***	0.053***	0.094***
	(0.012)	(0.014)	(0.015)
Observations	96437	96437	96358
R-squared	0.123	0.129	0.140

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The aggregate results mask potentially important differences between geopolitical blocs. The central question of this study is whether Chinese firms respond differently from firms headquartered elsewhere. Table 4 examines the heterogeneity in the estimated effects across the four geopolitical blocs.

Chinese firms stand out as the group exhibiting the most comprehensive adjustment of cross-bloc inventor networks. Greater exposure to fragmentation shocks is associated with a statistically significant decline in cross-bloc inventor bridges, a reduction in the share of inventors from rival geopolitical blocs, and a decrease in inventor bloc diversity. Taken together, these results indicate a broad decline in cross-bloc inventor integration among Chinese frontier firms as geopolitical fragmentation intensifies.

Firms headquartered in other Asian economies display a similar but less pronounced pattern. More exposed firms experience statistically significant declines in cross-bloc inventor bridges and the share of inventors from rival geopolitical blocs. Although inventor diversity also exhibits a negative coefficient, the estimate is only marginally statistically significant. Overall, the results suggest that fragmentation affects the geopolitical composition of inventor networks in other Asian economies, although the adjustments are less pronounced than those observed among Chinese firms.

For firms headquartered in the European Union, the strongest effect appears in the composition of the inventor teams. More exposed firms exhibit a substantial decline in the share of inventors from rival geopolitical blocs, whereas the estimated reduction in cross-bloc inventor bridges is only marginally statistically significant. In contrast, the diversity of inventors remains broadly unchanged. This pattern suggests a reconfiguration rather than a contraction of inventor networks, whereby collaboration with inventors from rival geopolitical blocs is reduced without a corresponding decline in the overall geographic diversity of inventive teams.

In contrast, firms headquartered in the United States exhibit little systematic response across the three measures. None of the estimated coefficients is statistically distinguishable from zero, suggesting that more exposed U.S. firms were able to maintain the structure and diversity of their inventor networks despite the broader decline in cross-bloc co-invention documented in the aggregate data.

Figures 5 and 6 report the dynamic shift–share estimates for conflict-bridge collaboration and inventor-bloc diversity. The coefficients measure the year-specific differences in the effect of fragmentation exposure relative to 2018. The estimates become systematically more negative after 2018, particularly for conflict-bridge collaboration, indicating that the adverse effect of fragmentation exposure on cross-bloc inventor integration strengthened as geopolitical tensions intensified.

Figure 5. Dynamic effects of shift-share exposure on cross-bloc innovation collaboration

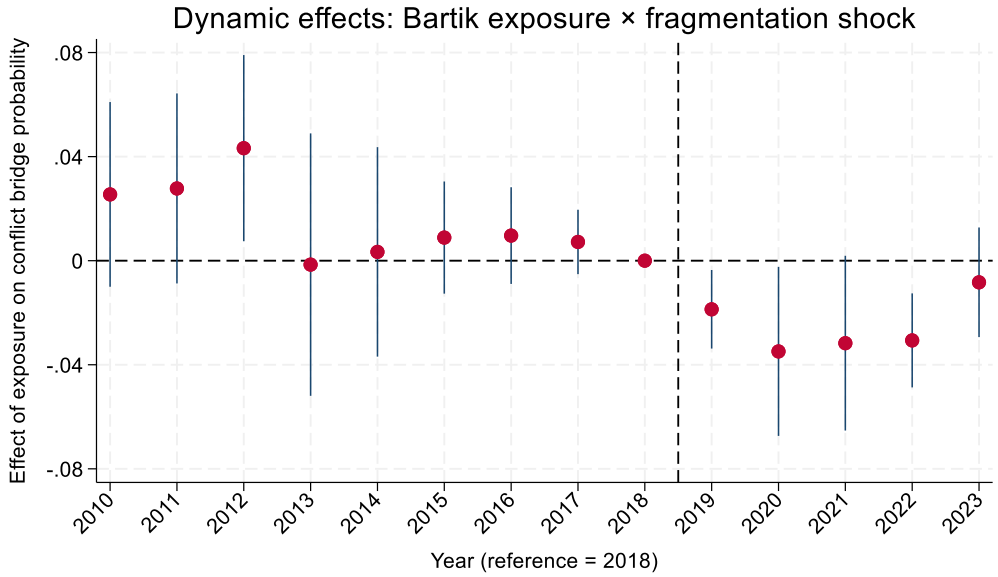
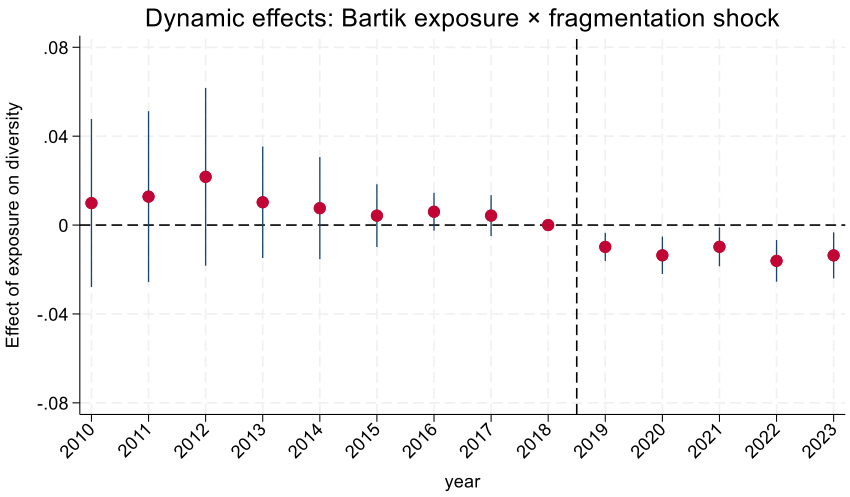


Figure 6. Dynamic effects of shift-share exposure on inventor-bloc diversity



5.2 Patent quality

Next, we examine whether firms with different pre-period exposure to cross-bloc inventor integration also experienced differential changes in patent quality as geopolitical fragmentation intensified. Table 5 reports the estimates for two complementary measures of patent quality: a breakthrough-patent indicator identifying patents in the top 5% of the forward-citation distribution within the application year and core 5G technology class and normalized log forward citations.

Columns (1) and (2) report the average relationships across all firms. Firms with greater pre-period exposure to cross-bloc inventor integration experienced larger increases in both the

probability of producing breakthrough patents and citation-based patent quality as geopolitical fragmentation intensified. However, these average estimates mask substantial heterogeneity across geopolitical blocs.

Table 5. Impact on patent quality

	(1) Breakthrough patents	(2) Patent quality	(3) Breakthrough patents	(4) Patent quality
Modified exposure × fragmentation shock (std)	0.008***	0.049***		
	(0.002)	(0.010)		
EU: Modified exposure × fragmentation shock (std)			-0.119	-0.757*
			(0.101)	(0.414)
US: Modified exposure × fragmentation shock (std)			-0.025*	-0.029
			(0.013)	(0.047)
China: Modified exposure × fragmentation shock (std)			0.006***	0.043***
			(0.002)	(0.009)
Asia (excl-CN): Modified exposure × fragmentation shock (std)			0.009***	0.008
			(0.002)	(0.011)
Constant	0.049***	0.425***	0.031***	0.336***
	(0.000)	(0.000)	(0.010)	(0.041)
Observations	96437	96437	96437	96437
R-squared	0.021	0.082	0.021	0.082

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The bloc-specific estimates indicate that the positive average relationship is primarily driven by Chinese firms. Among Chinese firms, greater pre-period exposure to cross-bloc inventor integration is associated with a higher probability of producing breakthrough patents and a

higher citation impact as geopolitical fragmentation intensifies. Among firms headquartered in other Asian economies, greater exposure is associated with an increase in breakthrough patenting, although no corresponding relationship is observed for the citation-based quality.

In contrast, European firms experience a decline in the quality of citation-based patents. The estimated coefficient is negative and statistically significant at the 10 percent level, suggesting that fragmentation may have reduced access to valuable external knowledge sources among European firms. However, no statistically significant effect was observed for breakthrough patenting. For U.S. firms, the breakthrough-patent estimate is negative and marginally significant, whereas the citation-impact estimate is small and statistically insignificant.

Overall, these results suggest that the relationship between geopolitical fragmentation and innovation quality is heterogeneous across geopolitical blocs. Although firms with greater pre-period dependence on cross-bloc inventor integration experience larger adjustments as fragmentation intensifies, the direction of these adjustments differs systematically across innovation systems. In particular, more exposed Chinese firms experience improvements in both breakthrough patenting and citation impact, whereas more exposed European firms experience a decline in the citation-based patent quality.

Given Huawei's dominant position in the sample (it accounts for approximately 13% of all sample patents and 46% of patents assigned to Chinese firms), we examine the robustness of our findings by excluding all Huawei patents from the estimation sample. As reported in the Appendix, the main qualitative conclusions remain unchanged.

5.3 Scientific collaboration networks

Next, we examine whether firms' scientific collaboration networks respond to geopolitical fragmentation. Table 6 reports the shift–share estimates for the university collaboration outcomes defined in Section 3.3.

Three results are noteworthy. First, greater exposure to fragmentation makes Chinese firms substantially more likely to work with universities: a one-standard-deviation increase raises the probability by 13.5 pp from a pre-2019 base of 56 percent and raises the probability of a domestic university partner by 16.1 pp. No other bloc shows a comparable movement, and U.S. firms move in the opposite direction on the domestic margin.

Second, the geography of collaboration shifts markedly. Among Chinese firms, the domestic share of university partners rises by 7.8 pp per standard deviation of exposure, and the rival bloc share falls by 4.5 pp, against a rival bloc share averaging 13 percent. In relative terms, the reweighting away from Western universities is the larger movement, at roughly a third of the mean, while the domestic share is bounded above by a base that already stood at 67 percent before 2019.

Table 6. Fragmentation exposure and university collaboration

	(1) Any university partner	(2) Any domestic university partner	(3) Any rival-bloc university partner	(4) Domestic share	(5) Rival-bloc share
China	0.135**	0.161***	0.002	0.078***	−0.045***
	(0.055)	(0.051)	(0.009)	(0.007)	(0.003)
United States	−0.016	−0.041**	−0.004	−0.027***	−0.002
	(0.015)	(0.018)	(0.003)	(0.008)	(0.004)
EU/UK	0.023	0.077	−0.034*	0.133***	−0.023
	(0.079)	(0.088)	(0.020)	(0.045)	(0.025)
Asia excl. China	−0.007	−0.006	−0.008**	0.006	−0.006*
	(0.011)	(0.011)	(0.003)	(0.004)	(0.003)
Observations	47821	47821	47821	34895	34895
R-squared	0.123	0.106	0.041	0.090	0.052

*Notes: All columns include firm and publication-year fixed effects, and no further controls. * p < 0.10, ** p < 0.05, *** p < 0.01.*

Third, the existence and composition margins of Western engagement move differently, as shown in Figure 3. The coefficient on having any rival bloc university partner is 0.002 with a standard error of 0.009, which bounds any change in the probability of Western academic engagement at well under two percentage points in either direction. That precise zero should not be read as stability, because the rival bloc for a Chinese firm pools the United States and Europe, and the two moved in opposite directions: descriptively, the share of Chinese firms' articles with a U.S. university partner falls from 9.2 to 5.9 percent between the pre-2019 and post-2018 periods, while the European share rises from 6.5 to 11.4 percent, leaving the combined Western indicator almost unchanged at 14.7 and 16.7 percent. Nonetheless, the composition margin moves against the West as a whole, and a share responds both to what is added at home and to what is withdrawn abroad; thus, column 5 cannot be decomposed into the two. Read together with Figure 3, the evidence points to substitution on two levels at once: Chinese firms shifted the center of gravity of their academic collaboration towards domestic universities, and within what remained abroad, they shifted from American towards European ones. Neither margin supports the stronger claim that Western academic ties were broken.

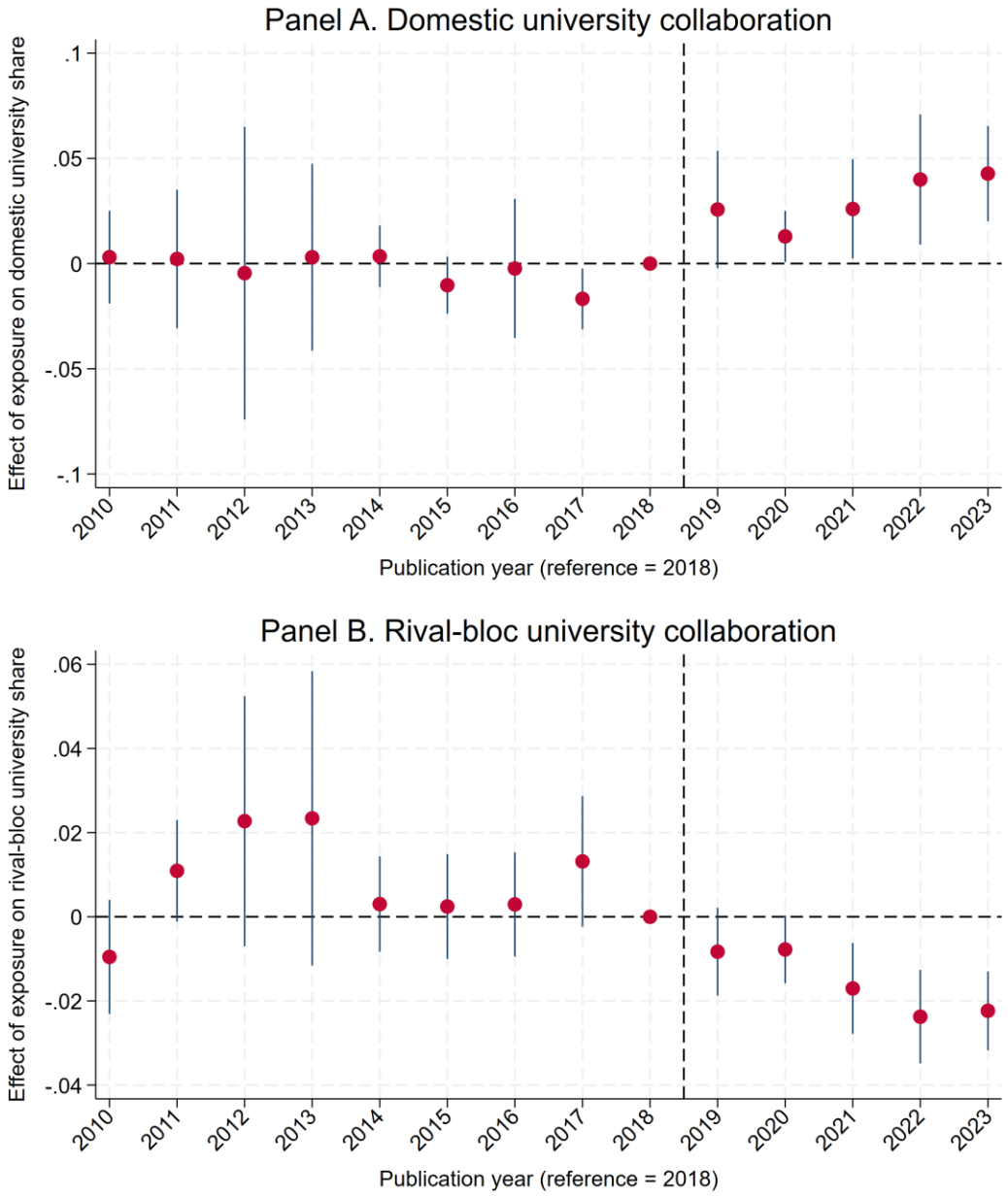
The other blocs moved differently and, in two cases, in the opposite direction. U.S. firms become less likely to have a domestic university partner, and their domestic share falls by 2.7 pp, consistent with the broadening of collaboration rather than a retreat homeward. Firms in Asia, excluding China, reduce rival bloc engagement on both the existence and share margin

without any offsetting domestic increase. European firms show a large positive coefficient on the domestic share, but we do not build a claim on it: the EU-side co-invention series that supplies the shift for European firms moves by 1.4 units over 2010-2023 against 42 units for the China-side series, so European exposure carries little identifying variation, and the remaining European coefficients are correspondingly imprecise.

Appendix Table A3 reports four specifications for each of the two composition measures and each of the two existence indicators: the baseline, a version adding field fixed effects, a version excluding Huawei, and a version restricting the sample to the four core 5G subfields, with the full set of bloc coefficients in every case. The rival bloc share result is the most robust of the four outcomes: it is unchanged by field fixed effects, survives the exclusion of Huawei, and holds in the tight 5G subfield sample. The domestic share results are weaker in one respect. Excluding Huawei leaves a coefficient of the same sign but reduces it by roughly a third, from 0.078 to 0.051, and renders it statistically indistinguishable from zero. Thus, domestic reorientation is concentrated in the largest Chinese firms rather than being uniform across them. The existence margins behave differently, with the domestic indicator strengthening rather than weakening when Huawei is removed. Therefore, we treat the reweighting away from rival bloc universities as the firmer of the two composition results.

Figure 7 reports event study estimates for the two composition measures, obtained by interacting pre-period exposure with publication-year indicators and omitting 2018, the year in which U.S. export controls on Chinese technology firms escalated. The design mirrors that of Figures 5 and 6 for patent outcomes. Neither panel shows a differential pre-trend: the pre-2019 coefficients fluctuate around zero without direction, and a test for a linear pre-trend gives -0.0005 ($p = 0.89$) for the domestic share and -0.0013 ($p = 0.15$) for the rival bloc share. From 2019 onwards, the two paths separate and move monotonically away from zero in opposite directions, reaching 0.043 for the domestic share and -0.022 for the rival bloc share by 2023. The timing is the one predicted by the design, and the magnitudes at the end of the period are close to the average post-2018 effects in Table 6. A stricter joint test that all pre-period coefficients equal zero is rejected, driven by year-to-year variation in the imprecisely estimated early years rather than any trend.

Figure 7. Event-Study Estimates: The Geography of University Collaboration



Notes: The reference year is 2018, and the vertical dashed line marks the escalation of U.S.–China technology restrictions. Vertical lines indicate 95% confidence intervals based on the standard errors clustered at the firm level. Both panels use articles with at least one university partner (34,895 firm–article observations).

Taken together, the publication evidence identifies a channel that patent data cannot observe. As cross-bloc inventive collaboration contracted, Chinese firms deepened their engagement with the domestic university system while remaining present in Western academic networks, so that the center of gravity of their scientific collaboration moved to their home country. Firms in the other blocs show no comparable reorientations. This asymmetry is consistent with the broader pattern observed among Chinese firms: those more exposed to fragmentation reduced cross-bloc inventive collaboration while simultaneously reorienting their scientific collaboration toward domestic universities.

6. Conclusions

This study examines how geopolitical fragmentation reshapes inventive and scientific collaboration and innovation outcomes in frontier 5G technology. Using a shift–share (Bartik) design applied to patent and publication data from leading 5G firms over 2010–2023, we examine whether firms with greater pre-period dependence on cross-bloc inventor integration adjust their inventive and scientific knowledge networks more strongly as geopolitical fragmentation increases.

These adjustments differ systematically across geopolitical blocs. Chinese firms exhibit broad and consistent reductions in cross-bloc inventor collaboration, while firms headquartered in other Asian economies display a similarly broad pattern. European firms show a more mixed pattern, with the strongest reduction in the rival bloc inventor share, whereas U.S. firms show little systematic change. At the aggregate level, the dynamic estimates become more pronounced after 2018, as geopolitical tensions intensify.

This study further finds that declining cross-bloc collaboration does not necessarily imply declining innovative performance. Although Chinese firms exhibited broad and consistent reductions in cross-bloc inventor integration, more exposed Chinese firms also exhibited a higher probability of producing breakthrough patents and higher citation-based patent quality. In contrast, more exposed European firms exhibit lower citation-based patent quality, whereas U.S. firms exhibit little systematic change. Publication data estimated using the same design show that the patent-based reorganization of Chinese firms' inventor networks coincided with a deepening of collaboration with domestic universities, without a corresponding decline in the probability of Western university collaboration. Taken together, patent and publication evidence suggests that geopolitical fragmentation was accompanied by a reconfiguration, rather than a contraction, of Chinese firms' knowledge networks.

One interpretation of these findings is that the observed reorientation reflects not only rising geopolitical fragmentation but also the maturation of China's innovation system. During the catch-up phase, extensive international collaboration may have contributed to the development of domestic scientific capabilities through the absorption and recombination of foreign knowledge (Fu, 2015), consistent with evidence that China's rise as a global scientific powerhouse was accompanied by rapidly expanding international collaboration and high-impact research, particularly in engineering and related scientific fields (Pisani et al., 2025). As this domestic knowledge base strengthened, Chinese firms may have become increasingly willing and able to rely on domestic educational institutions, whether in response to geopolitical constraints or as part of a broader strategic reorientation of knowledge-sourcing. This interpretation is also consistent with recent evidence that China's innovation system has evolved through increasingly dense linkages among firms, universities, research institutes, and local governments, thereby strengthening the domestic ecosystem for knowledge creation and diffusion (Sun & Kenney, 2024).

More broadly, the findings highlight the potential importance of domestic scientific and technological capabilities in shaping firms' responses to geopolitical fragmentation. Rather than imposing a uniform penalty on innovative performance, geopolitical fragmentation is associated with heterogeneous patterns of knowledge network reorganization across geopolitical blocs. The Chinese case, in particular, shows that declining cross-bloc inventive collaboration can coincide with stronger domestic scientific collaboration and sustained innovation performance.

Our findings also suggest that the costs of geopolitical distance are contingent and not uniform. While geopolitical fragmentation reduces cross-bloc inventor integration, its consequences for innovation depend on firms' ability to reorganize their knowledge networks. In this sense, geopolitical distance does not simply reduce the benefits of heterogeneous knowledge sources; it also changes the conditions under which different forms of knowledge heterogeneity become more sustainable.

These findings have implications for both innovation management and technology policy. For firms, geopolitical risk affects not only market access and supply chain resilience but also the organization of R&D and the composition of inventor teams. For policymakers, the results suggest that investing in domestic scientific capabilities may strengthen the resilience of innovation systems when international knowledge flows become politically constrained. More generally, the findings indicate that geopolitical fragmentation may reorganize, rather than simply contract, global innovation networks, with outcomes depending on the capacity of domestic innovation systems to support frontier innovation in the host country.

Future research should examine whether similar patterns emerge in other strategically important technologies, including semiconductors, artificial intelligence, and quantum technologies. Additional work is also needed to identify the organizational and institutional mechanisms through which firms adapt to geopolitical fragmentation and to assess the long-run consequences of these adjustments on global knowledge creation and technological progress.

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Appendix A. Robustness Analyses

Huawei accounts for approximately 13% of all patents in the sample and 46% of patents assigned to Chinese firms. To examine whether the results are driven by Huawei's dominant position, we re-estimate the heterogeneous-effects models after excluding all Huawei patents. Tables A1 and A2 show that the qualitative conclusions remain unchanged.'

Table A1. Bloc-specific heterogeneity in responses to geopolitical fragmentation: Excluding Huawei

	(1) Conflict bridge	(2) Conflict-bloc inventor share	(3) Diversity
China: Modified exposure × fragmentation shock (std)	-0.027***	-0.015***	-0.018***
	(0.003)	(0.004)	(0.004)
Asia (excl-CN): Modified exposure × fragmentation shock (std)	-0.025***	-0.029***	-0.021*
	(0.007)	(0.008)	(0.011)
EU: Modified exposure × fragmentation shock (std)	-0.170*	-0.440***	-0.023
	(0.099)	(0.107)	(0.128)
US: Modified exposure × fragmentation shock (std)	0.032	-0.001	0.018
	(0.023)	(0.017)	(0.030)
Constant	0.081***	0.046***	0.098***
	(0.014)	(0.015)	(0.018)
Observations	83988	83988	83915
R-squared	0.146	0.155	0.150

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A2. Robustness: Impact on patent quality excluding Huawei

	(1) Breakthrough patents	(2) Patent quality
China: Modified exposure × fragmentation shock (std)	0.004***	0.034***
	(0.001)	(0.006)
Asia (excl-CN): Modified exposure × fragmentation shock (std)	0.008***	0.003
EU: Modified exposure × fragmentation shock (std)	-0.136	-0.837**
	(0.095)	(0.395)
US: Modified exposure × fragmentation shock (std)	-0.027**	-0.038
	(0.013)	(0.047)
Constant	0.030***	0.337***
	(0.011)	(0.046)
Observations	83988	83988
R-squared	0.022	0.087

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A3. Robustness of the publication results

	(1)	**(2)**	**(3)**	**(4)**
	Baseline	+ field FE	Excl. Huawei	Core 5G only
Panel A. Domestic share of university partners				
China	0.078***	0.078***	0.051	0.072***
	(0.007)	(0.007)	(0.032)	(0.006)
United States	−0.027***	−0.026***	−0.028***	−0.024***
	(0.008)	(0.009)	(0.008)	(0.006)
EU/UK	0.133***	0.130***	0.133***	0.143**
	(0.045)	(0.046)	(0.045)	(0.053)
Asia excl. China	0.006	0.007	0.006	0.011***
	(0.004)	(0.005)	(0.004)	(0.004)
Observations	34895	34895	32148	17986
Panel B. Rival-bloc share of university partners				
China	−0.045***	−0.045***	−0.044***	−0.038***
	(0.003)	(0.003)	(0.006)	(0.005)
United States	−0.002	−0.002	−0.001	−0.005
	(0.004)	(0.004)	(0.004)	(0.004)
EU/UK	−0.023	−0.023	−0.021	−0.014
	(0.025)	(0.025)	(0.024)	(0.037)
Asia excl. China	−0.006*	−0.006*	−0.006*	−0.008***
	(0.003)	(0.003)	(0.003)	(0.003)
Observations	34895	34895	32148	17986
Panel C. Any domestic university partner				
China	0.161***	0.161***	0.392***	0.133**
	(0.051)	(0.051)	(0.138)	(0.060)
United States	−0.041**	−0.041**	−0.036**	−0.034**
	(0.018)	(0.018)	(0.013)	(0.013)

EU/UK	0.077	0.077	0.113*	0.111
	(0.088)	(0.087)	(0.066)	(0.094)
Asia excl. China	−0.006	−0.006	−0.001	0.001
	(0.011)	(0.011)	(0.009)	(0.010)
Observations	47821	47821	44640	24740
Panel D. Any rival-bloc university partner				
China	0.002	0.002	0.045*	−0.013
	(0.009)	(0.009)	(0.023)	(0.011)
United States	−0.004	−0.004	−0.002	−0.006*
	(0.003)	(0.003)	(0.003)	(0.004)
EU/UK	−0.034*	−0.033	−0.026	−0.019
	(0.020)	(0.020)	(0.016)	(0.038)
Asia excl. China	−0.008**	−0.008**	−0.007**	−0.010***
	(0.003)	(0.003)	(0.003)	(0.003)
Observations	47821	47821	44640	24740

*Note: Each panel reports one outcome. Column 1 presents the baseline specification of Table 6. Column 2 adds field fixed effects, column 3 excludes Huawei, and column 4 restricts the sample to the four core 5G subfields. All specifications include firm and publication-year fixed effects, and no further controls. Panels A and B are conditional on articles having at least one university partner. Standard errors are clustered by firm in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01.*