Information and Communication Technology and Firm Geographic Expansion

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Abstract

This paper studies how information and communication technology (ICT) affects firms' geographic organization and aggregate efficiency. Using confidential Census data on U.S. manufacturers, I show that ICT widens firms' geographic span of control by improving their internal communication. I then develop and estimate a quantitative spatial equilibrium model in which firms endogenously adopt technology, choose multiple production locations, and trade domestically. By exploiting natural experimental variation from the Internet privatization of the early 1990s, I quantify the channels through which technology reduces firm internal communication costs. Counterfactual analysis shows that Internet privatization increased overall efficiency by 1.7%, two-fifths of which came from firm geographic expansion. Policy simulations indicate that coordinated national policies yield greater gains in bridging the digital gap than local policies.

JEL Codes: D24, F12, O33, R30, L23

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1 Introduction

In recent decades, the geographic reach of U.S. firms has significantly expanded. Multi-unit firms—firms that operate in multiple locations—represent a large share of economic activities and drive numerous secular trends, such as rising industry concentration and wage inequality.[1] What drives this expansion? The advancement in information and communication technology (ICT) has been a prominent explanation (e.g. Hsieh and Rossi-Hansberg, 2023; Aghion et al., 2023). Empirical evidence on how ICT impacts firm location choices, however, remains scarce. Furthermore, despite large investments in ICT, little is known about the economic gains from technologies that enable firms to operate across multiple locations.[2]

This paper studies the fundamentals that drive firms' geographic expansion. I first use confidential data from the U.S. Census Bureau to document the importance of *internal communication technology*. Firms that adopt such technology are associated with greater geographic expansion. Consider Cemex, which is one of the world's largest manufacturers for building materials, for example. In the early 1990s, Cemex had fewer than ten plants in the U.S.; by 2012, it had expanded to over one hundred. This massive geographic expansion was powered by the aggressive adoption of ICT to improve internal communication. By the 1990s, the company connected all its global operations via a high-speed intranet, enabling headquarters to monitor daily production worldwide in real time (Dolan, 1998). Firms such as Cemex are not an exception but rather exemplify a widespread trend of technology-driven geographic expansion.

I then develop and estimate a spatial equilibrium model of heterogeneous firms to quantify the aggregate impacts of technology improvements. The model allows firms to endogenously adopt communication technology, choose multiple production locations, and trade domestically. Technology adoption improves firm production efficiency through two channels, namely, increasing firm-wide productivity and reducing internal communication costs between headquarters and production sites, enabling firms to expand geographically and locate closer to consumers. My findings show that the geographic expansion of multi-unit firms leads to widespread efficiency gains across locations. Ignoring this expansion would underestimate the efficiency gains from improvements in internal communication technology by 40%.

[1] According to the 2017 Economic Census, U.S. multi-unit firms account for more than 70% of sales and 60% of employment. Rossi-Hansberg et al. (2021) show that the increasing national concentration in the U.S. is driven by top firms operating more establishments across locations. Kleinman (2022) finds that the geographic expansion of multi-unit firms plays a significant role in increasing wage inequality.

[2] The OECD reports that investments in ICT amount to 30% of the U.S. nonresidential investment. Moreover, governments worldwide have launched numerous initiatives aimed at enhancing ICT infrastructure, such as the U.S. Infrastructure Investment and Jobs Act.

This paper uses confidential data from the U.S. Census Bureau, combining the Longitudinal Business Database with the 1999 Computer Network Use Supplement (CNUS) from the Annual Survey of Manufacturers. The CNUS provides detailed information on establishments' network adoption, covering specific technologies such as intranets, extranets, and local area networks, along with their communication patterns. Since technologies were more distinct and less integrated in the late 1990s, these data allow us to disentangle the specific channels through which ICT affects firm organization.

Using these data, I begin by presenting several motivating facts. Among various technologies, firms that adopt *intranets*—which represent a major technological breakthrough in internal communication enabled by high-speed internet—experience higher growth rates in their geographic span of control. Other technologies, such as extranets that are designed for external communication, do not predict geographic expansion. In addition, intranet adoption increases the likelihood of within-firm communication, further corroborating the role of declining internal communication costs in firms' geographic expansion.[3]

Motivated by these empirical findings, I propose a spatial equilibrium model of firm location choices and technology adoption. In the model, a firm chooses a set of locations to open establishments, with costly internal communication among those establishments. The firm balances benefits from proximity to consumers and potential cost savings against higher communication costs to headquarters and fixed setup costs. Notably, the model allows for either cannibalization or complementarity among a firm's establishments. Firms can adopt better technologies, such as intranets, to reduce their internal communication costs. This technology enhances production efficiency through two channels. First, it reduces headquarters–establishment communication costs that increase in distance. Second, it improves firm-wide productivity, affecting all its establishments equally. The first channel gives rise to rich interaction between technology adoption and firm internal geography, as the exact benefit from declining communication costs can vary depending on the firm's headquarters location, the other establishments' locations, and their proximity to markets.

Technology adoption affects firm geography on both the intensive and extensive margins. On the intensive margin, adopting internal communication technology disproportionally benefits remote establishments, leading the firm to allocate more sales and labor there. On the extensive margin, it allows geographic expansion. In the model, technology adoption and geographic expansion are complements. The benefit of expanding to more locations is greater if a firm adopts better technology; the benefit of adoption is also greater for a firm with a

[3]As a key advancement in communication technology, the adoption of intranets is commonly used in the business literature as a proxy for internal communication costs and has been linked to firm operations, such as plant managers' span of control (Bloom et al., 2014) and internal information precision (e.g. Azarmsa et al., 2023).

larger geographic span of control. In equilibrium, reducing the adoption cost has two countervailing effects: it increases the likelihood of adoption, which facilitates expansion, but it also intensifies market competition, which mitigates expansion. The net effect determines the geographic footprints of firms, which in turn shapes the distribution of efficiency gains from technology adoption across locations.

I estimate the model and quantify the two channels through which communication technology influences firm location choices: (i) reducing communication costs between headquarters and establishments, and (ii) increasing firm-wide productivity.

Using an intranet as a proxy for internal communication technology, I estimate the first channel by exploiting within-firm labor allocation across establishments for intranet adopters and nonadopters. This empirical strategy builds on the model's intensive margin implication that intranet adopters allocate more labor to distant establishments than nonadopters do, which means that they have a slower decline in establishment size over distance.[4] To account for the potential endogeneity of firms' intranet adoption, I exploit quasi-experimental variation from a major event in U.S. Internet history: the Internet privatization in 1995. This event significantly reduced the costs of accessing high-speed Internet and adopting Internet-enabled applications such as intranets.[5] Specifically, I instrument firms' intranet adoption by the distance from their headquarters to the nearest Internet backbone node. At locations closer to the nodes, infrastructure such as underground cables was more developed, leading to lower costs of adopting networks.[6] Indeed, firms with similar characteristics that were headquartered closer to the nodes were more likely to adopt intranets, whereas distance was not a strong predictor of the adoption of other types of networks. Those firms were also more likely to expand after the Internet privatization, especially toward locations near nodes. The estimates confirm that within-firm communication costs increase with distance and that the adoption of an intranet reduces the elasticity of communication costs with respect to distance by 50 percent.

To estimate the second productivity improvement channel, I use the method of simulated moments (MSM) to jointly estimate the increase in firm productivity associated with intranet adoption, alongside key parameters such as demand elasticity and the fixed costs of adoption

[4]Using U.S. Economic Census data, Bartelme and Ziv (2024) show that plant employment and sales decline with distance from headquarters, though this effect is weaker for large firms. They explain this pattern using a model where firms endogenously determine the productivity-distance elasticity.

[5]The history of U.S. Internet commercialization, including the deployment of Internet infrastructure, is reviewed and discussed in Greenstein (2015, 2020).

[6]As the construction and installation of circuits constitute major costs for Internet service providers, Internet access should be cheaper for locations with better infrastructure. The locations of Internet backbone nodes reflected historical contingencies regarding military concerns and proximity to research institutes and thus were less likely to be subject to contemporary shocks at the time of privatization.

and expansion. The results reveal a 30% improvement in firm effective productivity, as well as substantial fixed costs for intranet adoption and setting up establishments.[7] Overall, the estimated model is able to replicate the bilateral firm expansion patterns in the data well.

In the last part of the paper, I use the estimated model to quantify efficiency gains from improvements in internal communication technology. I begin with the 1995 Internet privatization used in estimation. I study this policy reform because it was one of the largest government ICT infrastructure projects in the U.S. Moreover, the late 1990s was the last period in which we observed significant aggregate productivity growth. I simulate this reform by lowering the cost of intranet adoption so that the model-implied change in the number of locations per firm matches my reduced-form estimate. Through the lens of the model, Internet privatization increases aggregate efficiency by 1.7% through improved internal communication. This efficiency gain accounts for a nontrivial share of the overall manufacturing productivity growth that occurred from 1996 to 2000.[8] Notably, 40% of this aggregate efficiency gain stems from firms' geographic expansion. The reduction in communication costs between headquarters and establishments accounts for another 25%, whereas the improvement in firm-wide productivity accounts for the remainder. Local efficiency gains range from 1.5% to 1.8%, and their distribution across locations is determined by the footprints of multi-unit firms and the entry and exit of their establishments.[9] These results underscore the importance of considering multi-unit firms and their endogenous location choices when assessing the benefits of ICT development.

I also use the model to study alternative policies to improve ICT access and reduce the digital divide. In particular, I compare a local policy, which reduces the cost in one specific location, and a national policy, which distributes the cost reduction across all locations. To capture the notion of bridging the ICT divide, the national policy provides greater cost reductions to locations with poorer ICT access. I find that the national policy yields a greater aggregate efficiency gain because of the cross-region spillovers through multi-unit production. In contrast, a trade-only model predicts that gains of these policies would be confined to the local level.

Governments worldwide have invested billions in ICT infrastructure initiatives, such as the U.S. Infrastructure Investment and Jobs Act, aiming to promote universal Internet ac-

[7] Draca et al. (2007) review a wide range of estimated output elasticities with respect to ICT capital, on the basis of studies using continuous ICT investment measures, but do not differentiate between specific technologies or adoption choices. Using German firm-level data on multinationals, Tintelnot (2017) estimates production efficiency losses of 5 to 35 percent.

[8] The Bureau of Labor Statistics (BLS) reports a 20.7% increase in manufacturing labor productivity between 1996 and 2000.

[9] Giroud and Mueller (2019) and Giroud et al. (2021) show that local shocks can spill over across locations through multi-unit firms.

cess. My results emphasize that gains from ICT improvements differ across locations and that firms' geographic organization in response to ICT adoption is important in shaping the gains from communication infrastructure development.

Relation to Literature. This paper contributes to three strands of literature. The first is the literature that investigates firm discrete location choices in general equilibrium, drawing from studies in international trade and economic geography (e.g., Tintelnot, 2017; Arkolakis et al., 2023; Oberfield et al., 2024; Antràs et al., 2024).[10] In particular, my model builds on and extends Tintelnot (2017), which treats communication costs as exogenous, a common assumption in the literature. My contribution is to illustrate, both empirically and quantitatively, that firm internal communication is endogenous to technology adoption and plays a crucial role in shaping their location choices. While not focused on technology adoption, Oberfield et al. (2024) introduces an endogenous span-of-control cost that increases with the number of establishments, which is reflected as a firm productivity shifter. In addition to this direct productivity channel, my model allows communication costs to vary with the distance of establishments from headquarters, where faraway establishments benefit most from reductions in communication costs. Consequently, the effects of cost reductions depend not only on the number of establishments but also on a firm's internal geography of its establishments. Furthermore, I use detailed microdata to quantify the productivity gains and communication cost reductions enabled by better internal communication technology.

Second, this paper contributes to the growing literature on firm expansion along the extensive margin (Cao et al., 2019; Hsieh and Rossi-Hansberg, 2023; Aghion et al., 2023; Kleinman, 2022). For example, Aghion et al. (2023) develop a model in which large firms expand into a broader set of product lines, benefiting from lower overhead costs and greater efficiency advantages. Hsieh and Rossi-Hansberg (2023) argue that the introduction of a new fixed-cost technology reduces the marginal costs of firms operating across multiple locations. Many of these studies highlight the rise of ICT as a key example of such transformative technology. However, empirical evidence remains limited. One exception is DeStefano et al. (2023), which use U.K. data to show that cloud services enable firms to establish operations in more locations and reallocate employees to distant establishments, which aligns with my findings. My paper contributes to this literature by identifying internal communication as a specific mechanism through which ICT drives firm expansion. Additionally, reduced-form analysis that exploits plausibly exogenous variation from Internet privatization provides further empirical support.

[10] Firm discrete location choice is a classic problem in operation research and has been studied in the industrial organization literature (e.g. Jia, 2008; Holmes, 2011). However, these studies often do not consider general equilibrium effects.

Third, this paper adds to the long-standing literature on the benefits of ICT improvements, particularly in relation to firms' span of control.[11] Bloom et al. (2014) show that communication technology can have effects distinct from those of information technology, with ambiguous implications for plant managers' span of control, although they do not address the firm-wide span of control due to data limitations. Fort (2017) demonstrates that adopting electronic networks facilitates vertical fragmentation but does not differ among specific technologies. Leveraging rich data on the adoption of various networks and firms' geographic footprints, this paper focuses on the drivers of firms' horizontal expansion across locations. Moreover, I quantify the aggregate efficiency gains from improved internal communication technology in equilibrium. To this end, this paper complements recent studies that use microdata to assess how falling ICT costs influence numerous macroeconomic trends, such as wage inequality across cities (e.g. Rubinton, 2020; Eckert et al., 2020) and increases in industry concentration (e.g. De Ridder, 2024; Lashkari et al., 2024; Jiang and Rubinton, 2024).[12] This paper focuses on the geographic expansion of firms by incorporating location choices and technology adoption into a spatial equilibrium model that matches observed firm expansion patterns across locations. I show that efficiency gains depend on firms' location choices and that ignoring these choices significantly underestimates the benefits of communication technology.

Paper Outline. Section 2 describes the dataset sources and presents motivating facts. Section 3 develops the model, followed by the structural estimation in Section 4. Section 5 presents policy simulations, and Section 6 concludes.

[11] A long line of research has studied the implications of ICT for firm performance at the micro level and productivity growth at the macro level (e.g., Jorgenson, 2001; Jorgenson et al., 2003; Stiroh, 2002; Oliner and Sichel, 2000; Brynjolfsson and Yang, 1996; Brynjolfsson and Hitt, 1996, 2003; Dedrick et al., 2003; Aral et al., 2006; Draca et al., 2007; Bloom et al., 2012; Baslandze, 2016; Kneller and Timmis, 2016; DeStefano et al., 2018). See Bresnahan (2010) and Goldfarb and Tucker (2019) for reviews of general-purpose technology and recent developments in digital economics.

[12] Although not based on microdata, Aghion et al. (2023) use a calibrated model to show that reducing overhead costs increases short-run U.S. efficiency by 2%. Using U.S. microdata, De Ridder (2024) finds that cost reductions from intangibles increase the short-run U.S. growth rate from 1.3% to 1.6%. Using French data, Lashkari et al. (2024) find that falling IT prices boost aggregate output by 1.4% to 3.9%. In addition to these macro studies, many empirical studies focus on the reduced-form effects of technology on local market outcomes (e.g., Forman et al., 2012; Falck et al., 2014; Akerman et al., 2015; Steinwender, 2018; Juhász and Steinwender, 2018; Hjort and Poulsen, 2019; Akerman et al., 2022; Hanlon et al., 2022).

2 Data and Empirical Motivation

2.1 Data Sources

Computer Network Use Supplement (CNUS). Data on ICT adoption come from the CNUS, which is a supplement to the 1999 Annual Survey of Manufacturers (ASM). Establishments in the CNUS constitute 50% of US manufacturing employment and 60% of shipment value.

The purpose of this survey is to understand e-commerce activities and e-business process use at that time. The key set of variables for this paper pertains to network adoption; the CNUS asks establishments whether they use the Internet, an intranet, a local area network (LAN), an electronic data interchange network (EDI), an extranet, or other networks. These network adoption variables are key to identifying different channels through which technology can facilitate firms' geographic expansion. For example, an intranet—a private internal network that focuses on sharing information and smoothing communication among members inside the firm—reduces within-firm communication costs, while an extranet—a private network that links the firm to its customers and suppliers—expedites businesses with external parties. Compared with modern technologies, those from the late 1990s were more distinct and less integrated, which enables us to isolate the specific mechanisms through which ICT influences firm operation. Although specific to manufacturing firms, these technologies are widely used in various sectors, such as retail, wholesale, and banking, and their roles in firm location choices are of broader interest beyond manufacturing.

In addition to the network adoption items, the survey asks whether the establishment uses online networks (i.e., Internet, intranet, EDI, or extranet) to share information with other units in the company, external customers, or external suppliers.[13] Appendix A.1 provides more details on these data.

The CNUS provides detailed insights into different types of networks and the distinct channels of ICT. However, one limitation is the lack of data on usage intensity or expenditures. Most available expenditure data pertain to more aggregate ICT categories, such as hardware and software. Nevertheless, binary technology adoption data have been used in studies to identify specific economic mechanisms (e.g. Bloom et al., 2012; Fort, 2017; McElheran, 2015; Forman and McElheran, 2024; DeStefano et al., 2023).[14] Another limitation is

[13]Using the CNUS data, Fort (2017) shows that establishments with electronic networks are more likely to outsource their production; Atrostic and Nguyen (2005) shows a positive relationship between the use of electronic networks and labor productivity; Forman and McElheran (2024) finds that the use of an external network led to a reduction in downstream vertical integration.

[14]A recent Census survey, namely, the Annual Business Survey, collects adoption data for a wide range of technologies, including some limited measures of usage intensity (Zolas et al., 2021).

that the survey was conducted in only one year. However, since most of these technologies rely on high-speed internet, which became widely available after 1995, adoption in 1999 likely reflects changes since that time.

Longitudinal Business Database (LBD). I merge the CNUS data with the LBD, which covers all U.S. establishments. The LBD provides longitudinal establishment and firm identifiers, enabling me to track firms' geographic footprints over time. It also includes establishment details such as ZIP code, county, state, employment, payroll, and industry.[15]

I focus on firms' geographic expansion within industries, i.e., horizontal expansion. Recent studies have shown that overall firm expansion is driven by within-industry expansion across locations rather than across industries.[16] To measure within-industry expansion, I consider the establishments that a firm owns in a given industry at the six-digit NAICS level. Specifically, I define a firm as a FIRMID-industry pair, referred to as a *firm* hereafter. This approach allows me to focus on firms' expansion across locations and abstract from changes in industry composition. Robustness checks confirm that the findings remain qualitatively consistent when FIRMID is used or when the analysis is restricted to single-industry firms.

The primary measure of a firm's geographic span of control is the number of establishments it operates. As shown in Figure 1, the average number of establishments per firm for multi-unit firms increased significantly from 1977 to 2012. This increase reflects firms' expansion into broader geographic regions. Other measures—e.g., the number of counties, states, and census divisions in which firms have establishments—show a similar trend. Notably, this trend is not driven by selection bias; the pattern persists even when the sample is restricted to incumbent firms that keep operating in an industry throughout the period. Appendix Section B.2 further explores how this geographic expansion aligns with broader changes in the manufacturing sector, including trends in employment and industry scope.

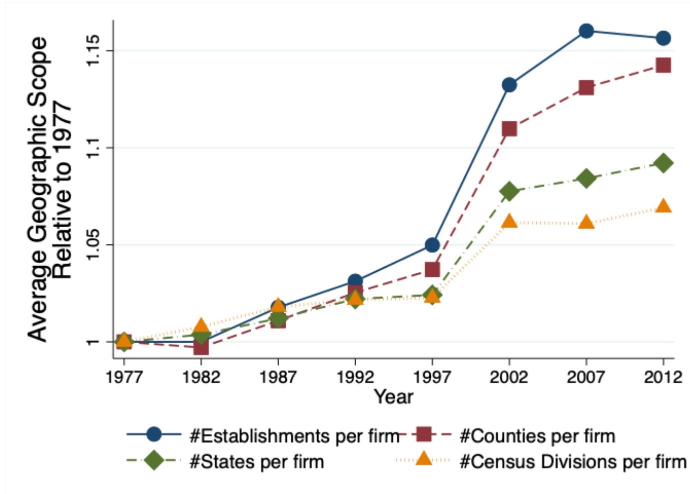
Given that multi-unit firms account for a substantial share of U.S. employment, understanding the impact of ICT on their geographic span of control has important aggregate implications.

I also aggregate the establishments' network adoption and communication to the corresponding firm level, assuming that a firm has adopted certain networks and communicates

[15] I exclude noncontiguous U.S. states, i.e., Alaska, Hawaii, Puerto Rico and the U.S. Virgin Islands. As the industry classification system experienced a major change in 1997 and has been updated constantly, I use the consistent industry codes provided by Fort and Klimek (2018).

[16] While firms expand to more locations over time, they tend to specialize in fewer industries. Hsieh and Rossi-Hansberg (2023) report that top firms in the U.S. have reduced their sectoral coverage, reflecting increasing specialization. Ekerdt and Wu (2022) documents specialization in U.S. manufacturing. Similarly, Ma (2022) shows that firms, particularly those engaging in R&D activities, have decreased their number of industries.

Figure 1: Geographic Scope of U.S. Multi-Unit Manufacturers from 1977 to 2012



Notes: This figure shows the average number of establishments, counties, states, and census divisions in which a firm has operation for multi-unit manufacturing firms from 1977 to 2012. Data source: Longitudinal Business Database (LBD).

with internal and external parties if one of the firm's establishments does so. Nevertheless, my empirical results are robust to alternative aggregation methods, such as taking averages across the firm's establishments and using establishment-level ICT adoption and communication patterns.

Census of Auxiliary Establishments (AUX). I use the AUX, which covers nonproduction establishments of multi-unit firms such as their R&D centers and corporate headquarters, to identify headquarters for firms with standalone headquarters. For firms with integrated headquarters, I follow the approach of Aarland et al. (2007) and Giroud (2013) by designating the establishment with the largest payroll as the headquarters.[17]

Samples and summary statistics. The following empirical analysis uses the CNUS–LBD linked data. As the CNUS data do not include nonmanufacturing firms, my main analysis focuses on manufacturing firms and their establishments. Table 1 presents summary statistics. The variables regarding ICT delineate the state of technology adoption at the end of the twentieth century. Although the basic Internet adoption rate was high at this time, adoption rates for advanced technologies such as intranets and EDIs, which relied on high-speed Internet and sophisticated infrastructure, were low.[18] Approximately 36% of the firms

[17]Appendix A.3 provides details of how I identify firm headquarters.

[18]Appendix Table A.1 reports comparable adoption rates of different technologies and communication patterns at the establishment level. Forman et al. (2003) and Forman et al. (2012) use the Harte-Hanks Market Intelligence CI Technology database and document similar patterns of a high adoption rate for the basic Internet but a relatively low rate for Internet-enabled applications that enhance business processes.

Table 1: Summary Statistics

	N	Mean	S.D.
ICT Adoption			
Internet	18,500	0.726	0.446
Intranet	18,500	0.307	0.461
Electronic data interchange (EDI)	18,500	0.235	0.424
Extranet	18,500	0.070	0.254
Local area network (LAN)	18,500	0.641	0.480
Others	18,500	0.058	0.234
Communication			
Within Firm	18,500	0.338	0.473
Customers	18,500	0.294	0.456
Suppliers	18,500	0.533	0.499
Other Firm Characteristics			
Multi-unit firm	18,500	0.357	0.479
Number of establishments	18,500	2.317	4.262
Number of workers	18,500	322.6	1128
Salary and wages (in thousands)	18,500	12790	59530
Sales (in thousands)	18,500	103200	829800
Capital (in thousands)	18,500	41350	233100

Notes: Summary statistics of firms in the Computer Network Use Supplement (CNUS) to the 1999 Annual Survey of Manufactures. Each firm is a FIRMID×6-digit NAICS industry pair. Variables regarding ICT adoption and communication are indicators.

in the CNUS sample are multi-unit, with 2.3 establishments on average. While the data tend to cover larger firms, particularly multi-unit firms, these firms have substantially enlarged their geographic scope. Rich data on their ICT adoption help us study how ICT impacts their geographic expansion.

Later, the estimation, particularly the reduced-form analysis of Internet privatization, relies on a balanced panel from the LBD during 1987 and 2007. Appendix A.2 provides a more detailed description of this sample.

2.2 Empirical Motivation

2.2.1 ICT Adoption and Geographic Expansion

I begin by estimating the correlation between firms' adoption of different networks and their geographic expansion using the following regression:

$$\Delta \widehat{\text{NumEstab}}_{i,97-02} = \alpha + \text{Networks}_{i,99}\beta + X_{i,97}\gamma + \varepsilon_{i,97-02} \quad (1)$$

where the dependent variable is the five-year growth rate in the number of manufacturing establishments of firm i from 1997–2002, measuring the firm's geographic expansion around 1999. $\text{Networks}_{i,99}$ is a vector of indicators this is set to one if the firm installed an intranet, an EDI, an extranet, the Internet, or a LAN. I also control for initial log employment, fixed effects of firm age, state, and four-digit NAICS industry.

Panel A in Figure 2 (solid circles) displays the coefficient for each type of network. It shows that *intranet* adoption is associated with a higher growth rate in the number of establishments of firms. Table B.1 reports the regression results. The estimated coefficient on Intranet suggests that having an intranet installed by 1999 is associated with a 3-percentage-point larger growth rate in a firm's number of establishments from 1997 to 2002. If we take into account that the average growth rate was 4.7 percentage points during this period, the estimated coefficient is equivalent to a 64% increase. In contrast, the coefficients for the other networks are statistically insignificant and economically small. This comparison suggests that enhancing internal communication, which an intranet is designed to do, plays an important role in the geographic expansion of firms.[19]

In addition, I consider firms' overall expansion across all sectors. Specifically, I calculate the number of establishments linked to the same FIRMID, regardless of their industries, and relate their 5-year growth rate to the adoption of various networks. Recent studies have shown that incumbent manufacturers have increased their nonmanufacturing employment by opening new establishments (Fort et al., 2018). Consistent with this, the triangle markers show that firms that adopt online networks are associated with greater expansion in all sectors. Besides intranets, the other networks also display positive coefficients, although their coefficients are smaller or insignificant.

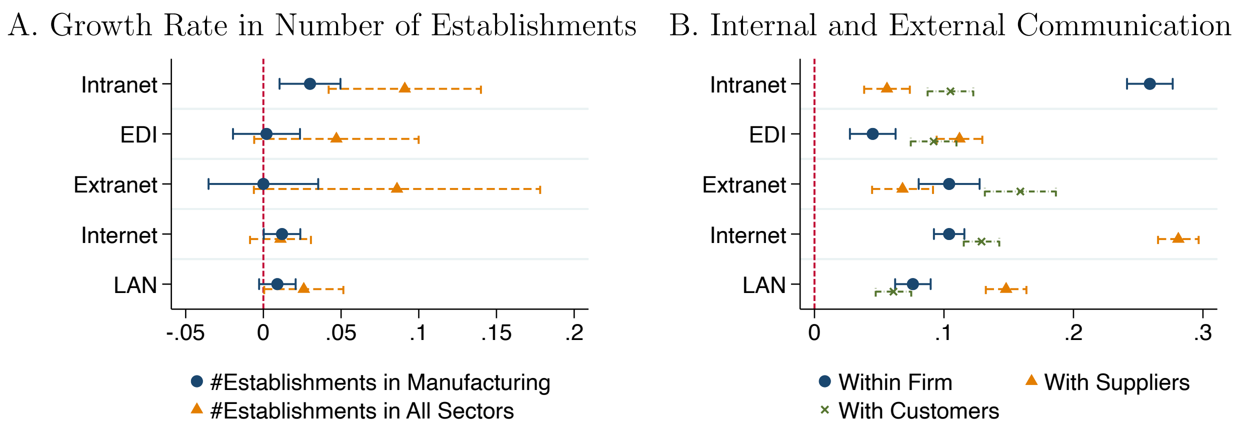
Several caveats are worth noting. First, these relationships are correlations and may not be causal. For example, firms that plan to expand might have a greater incentive to adopt an intranet, leading to reverse causality. In Section 4, I exploit plausibly exogenous variation in firms' ICT adoption and show that firms with greater ICT cost reduction experience greater expansion. Second, since the network data are available only for 1999, some firms classified as nonadopters in that year may adopt these networks later, potentially increasing their geographic scope and thus weakening the observed correlation between adoption and growth rates. If so, my estimate may be downward biased.

2.2.2 ICT Adoption and Within-Firm Communication

To further corroborate the role of intranets in within-firm communication, I leverage variables from the 1999 CNUS data on firms' communication patterns. I do so by estimating the same regression as Equation (1) but replacing the dependent variable with an indicator set to one

[19] The introduction of intranets marked a significant innovation in internal business communication. Using Harte-Hanks, a proprietary dataset on firm ICT usage, Forman (2005) reports that commercial intranet adoption by businesses tripled from 1996 to 1998.

Figure 2: ICT Adoption, Expansion, and Communication



Notes: Panel A displays the regression coefficients of Equation (1). The dependent variables are the 5-year growth rates in the number of establishments in manufacturing (circle) and in all sectors (triangle). Panel B displays the coefficients of regressions of the same form but replaces the dependent variable with an indicator for communication within the firm (circle), with external suppliers (triangle), and with external customers (cross). Confidence intervals are at the 95% level.

if any establishment of firm i shares information with other company units.

Panel B in Figure 2 confirms that intranets are the most important network for within-firm communication, with an estimated coefficient more than double that of other types of networks. In contrast, intranets have a limited effect on firms' external communication. In Panel D, the dependent variables corresponding to the triangles and crosses are indicators set to one if a firm communicates with external customers and suppliers, respectively. Extranet adoption is the most important for customer communication, and the Internet is the most important for supplier communication. It is reassuring that intranets play a small role in firms' external communication, suggesting that their large effect on internal communication—and geographic expansion—is not merely driven by unobserved firm characteristics.

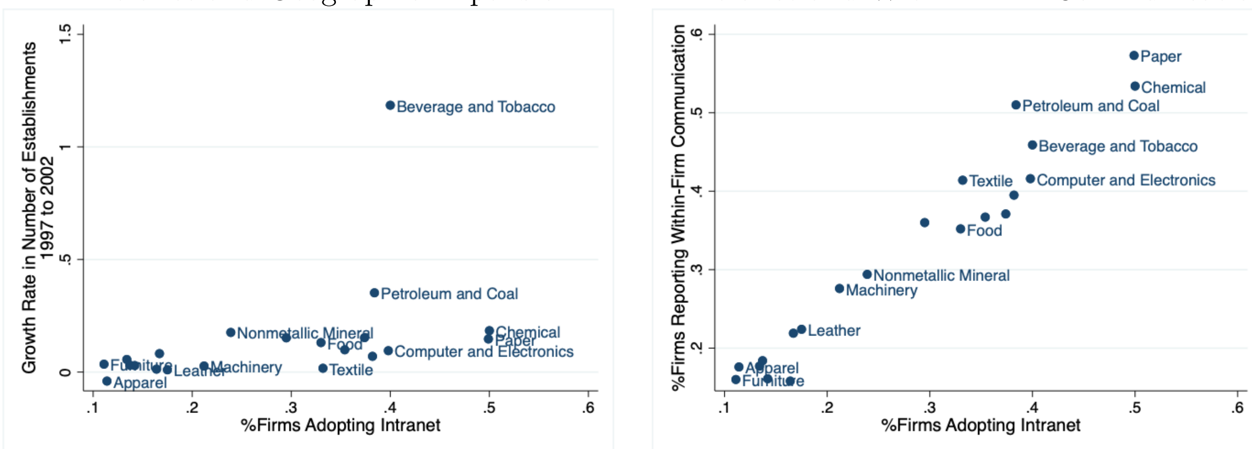
As the CNUS provides network adoption and communication patterns at the establishment, I further exploit within-firm variation across establishments by controlling for firm fixed effects. Table B.3 reports the regression coefficients. The findings align with those of the firm-level analysis and highlight the importance of intranets for within-firm communication.

2.2.3 Industry Heterogeneity

Internal communication costs may vary across industries. For example, ready-mix concrete producers such as Cemex, with higher shipping costs and proximity needs to consumers, may face higher internal communication costs. Intranets can thus have a greater impact on these industries.

Figure 3: Intranet, Expansion, and Within-Firm Communication: By Industry

A. Intranet and Geographic Expansion B. Intranet and Within-Firm Communication



Notes: These figures plot 3-digit NAICS industries' average 5-year growth rates in the number of establishments (Panel A) and industry shares of firms sharing information within the firm (Panel B) against shares of firms adopting intranets. Weights provided by the ASM are applied in calculating averages.

Panel A of Figure 3 plots the industry average 5-year growth rate in the number of establishments against its share of firms adopting intranets. Industries with higher shipping costs, such as the beverage and tobacco, petroleum and coal, and chemical manufacturing industries, have greater adoption rates of intranet, as well as a greater degree of geographic expansion. Panel B confirms a strong positive correlation between the industry intranet adoption rate and the likelihood of firms sharing information within the firm. Again, paper and chemical manufacturing—as industries with higher shipping costs—stand out in terms of higher adoption rates of intranets and a greater need for internal communication.

Overall, the empirical evidence shows that intranet adoption, which reduces internal communication costs, is associated with greater likelihood of within-firm communication and geographic expansion. In the following section, I incorporate these findings in a structural model to provide a framework to quantify the gains from improvements in internal communication technology in equilibrium.

3 A Model with Multi-Unit Firms and ICT Adoption

I incorporate endogenous within-firm communication costs into a spatial equilibrium model in which firms can produce goods in multiple locations.

The economy consists of N locations, denoted by $\mathscr{N} = \{1, 2, \cdots, N\}$. In the following, I use the terms "location" and "market" interchangeably. Each location $s \in \mathscr{N}$ is inhabited by a representative consumer and a continuum of firms born in that location $i \in [0, m_s]$, where m_s is the exogenous mass of the firms in location s. The representative consumer sells labor in a perfectly competitive market and maximizes a CES utility. The settings for firms follow Tintelnot (2017), assuming that each firm i produces a continuum of differentiated varieties $\omega \in [0, 1]$ that are tradable across locations. Each product is then indexed by a firm-variety combination (i, ω) and can be produced at different establishments of the firm. Firms compete monopolistically in each product market.

I refer to a firm's birth location as its "headquarters" and denote it by o. The firm's additional establishment locations are denoted by s, and destination markets are denoted by k.

I refer to a firm's birth location as its "headquarters" and denote it by o. The firm's additional establishment locations are denoted by s, and destination markets by k.

3.1 Demand

The representative consumer in each market k maximizes a CES utility that aggregates outputs y_{iok} from all firms i in the economy:[20]

$$U_k = \left(\sum_{o=1}^{N} \int_0^{m_o} y_{iok}^{\frac{\sigma-1}{\sigma}} \, di \right)^{\frac{\sigma}{\sigma-1}}, \tag{2}$$

where y_{iok} is the amount of output shipped to market k by firm i that is headquartered at o, and σ is the elasticity of substitution *across firms*. For each firm i, its output is in turn a CES aggregate of all varieties the firm produces $\omega \in [0, 1]$:

$$y_{iok} = \left(\int_0^1 y_{iok}(\omega)^{\frac{\rho-1}{\rho}} \, d\omega \right)^{\frac{\rho}{\rho-1}}, \tag{3}$$

where ρ is the elasticity of substitution *within a firm* across varieties.

The demand for variety ω produced by firm i is then given by:

$$y_{iok}(\omega) = p_{iok}(\omega)^{-\rho} p_{iok}^{\rho-\sigma} P_k^{\sigma-1} E_k, \tag{4}$$

where $p_{iok} = \left(\int_0^1 p_{iok}(\omega)^{1-\rho} d\omega \right)^{\frac{1}{1-\rho}}$ is the firm-specific price index that summarizes prices charged to market k for all varieties produced by firm i, $P_k = \left(\sum_{o=1}^{N} \int_0^{m_o} p_{iok}^{1-\sigma} di \right)^{\frac{1}{1-\sigma}}$ is the ideal price index in market k, and E_k is total expenditure on manufacturing goods.

[20] All varieties are available to all markets, abstracting away the fixed cost of exporting.

3.2 Production Technology

Firms are endowed with a headquarters in their birth location and can set up additional establishments elsewhere, up to one per location. Products are produced at *establishments*, using a constant-returns-to-scale production function with labor as the only input. An establishment s of firm i, headquartered in o, produces y_{ios} units of variety ω according to the production function: $y_{ios}(\omega) = z_i \varepsilon_{is}(\omega) l_{ios}(\omega)/\gamma_{ios}$. Here, z_i is firm-specific productivity that affects all its establishments and is iid across firms. $\varepsilon_{is}(\omega)$ is establishment-specific productivity, which is drawn iid from a location-specific Fréchet distribution $F_s(\epsilon) = \exp(-(\epsilon/T_s)^{-\theta})$. The scale parameter T_s determines the state of technology at location s, and the shape parameter θ determines the dispersion of establishment productivity draws. $l_{ios}(\omega)$ is the local labor input.

Internal communication. γ_{ios} is an iceberg-type communication cost from establishments to headquarters that varies with the firm's adoption of communication technology, denoted by $\varphi_i \in \{\underline{\varphi}, \overline{\varphi}\}$. In the following, I work with simple yet flexible communication technology, which decomposes γ_{ios} into two terms:

$$\gamma_{ios} = \gamma_{os}(\varphi_i) = \underbrace{h(\varphi_i)}_{\text{firm-wide}} \quad \underbrace{d_{os}(\varphi_i)}_{\text{HQ-establishment}} \tag{5}$$

The first term reflects firm-wide communication costs and acts as a shifter of firm productivity. The second term captures the communication costs between headquarters and establishments.[21] For example, longer distances can increase monitoring costs and complicate management. Gumpert et al. (2022) shows that internal geographic frictions of multi-unit firms increase the number of managerial layers of the firm. Motivated by the empirical evidence, I assume that adopting internal communication technology (i.e., $\varphi_i = \overline{\varphi}$) reduces both types of costs.

Variable costs. The unit cost for firm i producing variety ω at location s and shipping to market k is:

$$c_{iosk}(\omega) = \underbrace{(z_i/h(\varphi_i))^{-1}}_{\substack{\text{firm effective}\\ \text{productivity}}} \ \underbrace{(\varepsilon_{is}(\omega))^{-1}}_{\substack{\text{local}\\ \text{productivity}}} \ \underbrace{w_s}_{\substack{\text{input}\\ \text{cost}}} \ \underbrace{\tau_{sk}}_{\substack{\text{shipping}\\ \text{cost}}} \ \underbrace{d_{os}(\varphi_i)}_{\substack{\text{communication}\\ \text{cost}}} \ . \tag{6}$$

This expression helps understand why firms expand. They would like to tap into locations with high levels of local productivity ε_{is}, low input costs such as wages w_s, and minimal

[21] Specifically, $h(\varphi_i) \geq 1$ and $d_{os}(\varphi_i) \geq 1$. Local production does not incur the second type of cost, $d_{oo}(\varphi) = 1$.

shipping costs to reach consumers τ_{sk}. However, expanding to distant locations increases communication costs with headquarters d_{os}.

Adopting communication technology lowers variable production costs through two channels. First, it enhances firms' effective productivity, as reflected by $1/h(\overline{\varphi}) \geq 1/h(\underline{\varphi})$. Second, it reduces the communication costs between headquarters and establishments, $d_{os}(\overline{\varphi}) \leq d_{os}(\underline{\varphi})$ for $s \neq o$. Quantifying the impact of these channels is essential for assessing the benefits of technology adoption on production efficiency, which I address in the estimation section.

Fixed costs. Firms face a fixed cost f^X_{ios} when they set up additional establishments besides headquarters, with this cost depending on the locations of the establishment and headquarters. Additionally, firms pay a fixed cost f^{ICT}_{io} if they choose to adopt better communication technology, and this cost varies across headquarters locations. Both fixed costs are firm-specific to reflect the varying expansion and technology adoption decisions for firms with similar characteristics in the data. As the fixed costs and their forms are unobservable from data, I assume that they are paid in the numeraire with the same price across locations.

3.3 Firm Optimization Problem

Firms decide whether to adopt better technology to improve internal communication, choose optimal sets of production locations, produce a continuum of varieties, and serve markets. I first derive the firm's profit, given establishment locations and technology status. I then solve for the optimal locations and technology adoption. Appendix C provides a detailed model derivation.

3.3.1 Production Given a Set of Establishment Locations and Technology

To ease notation, I now index firms headquartered at o by their productivity z. Let the firm's set of locations S and its communication technology φ be fixed.

For each market k and each variety, the firm chooses one of its establishments $s \in S$ that has the lowest unit cost, as defined in Equation (6), to serve the market. Using the Fréchet distribution properties for establishment productivity ε and the CES demand, we can integrate over the profit of all varieties and derive the firm's profits from market k:

$$\pi_{ok}(S, \varphi, z) = \frac{\sigma^{-\sigma}}{(\sigma - 1)^{1-\sigma}} \tilde{\Gamma} E_k P_k^{\sigma-1} \left(\frac{z}{h(\varphi)} \right)^{\sigma-1} \Phi_{ok}(S, \varphi)^{\frac{\sigma-1}{\theta}}, \tag{7}$$

where $\tilde{\Gamma} \equiv \Gamma\left(\frac{\theta+1-\rho}{\theta}\right)^{1/(1-\rho)}$ is a constant,[22] and $\Phi_{ok}(S,\varphi)$ is the firm's "*production potential*" for serving market k, given by

$$\Phi_{ok}(S,\varphi) \equiv \sum_{s\in S}(T_s/w_s)^{\theta}\tau_{sk}^{-\theta}d_{os}(\varphi)^{-\theta}. \tag{8}$$

This term summarizes the states of technology T_s and wages w_s of all the firm's establishment locations, the shipping costs to market k from these establishments τ_{sk}, and the communication costs to headquarters $d_{os}(\varphi)$, which are endogenous to the firm's internal communication technology.

The firm's production potential $\Phi_{ok}(S,\varphi)$ increases with its technology φ and with its set of establishments S. Therefore, firms are incentivized to expand geographically to increase their production potential, thereby increasing profits. The extent to which firm profits increase due to increased production potential depends on the strength of within-firm cannibalization or complementarity, which is determined by demand elasticity σ and the shape parameter of the Fréchet distribution θ, as Equation (7) indicates. On the one hand, when an establishment is added, the production potential improves so that the firm can charge a lower price, increasing total sales and subsequently sales across all establishments. The strength of this effect depends on demand elasticity σ, where a higher value implies a greater inclination of consumers toward lower-priced firms and thus larger complementarity. On the other hand, a larger θ indicates a smaller dispersion of establishment shocks, resulting in establishments becoming closer substitutes. Adding an establishment thus reduces sales from existing establishments. When $\sigma - 1 < \theta$, the latter force dominates, leading to within-firm cannibalization. When $\sigma - 1 > \theta$, the former force dominates, and the firm's establishments are complements. I allow either case and later use data to discipline the relationship between σ and θ.[23]

Moreover, the adoption of internal communication technology increases firm profits by increasing the firm's effective productivity, $z/h(\varphi)$, and its production potential by reducing internal communication costs $d_{os}(\varphi)$. The latter allows for a rich interaction between technology adoption and firm internal geography. The exact increase in production potential from ICT relies on the firm's headquarters, the set of establishment locations, and market proximity from these establishments.

[22] I assume that $\rho - 1 < \theta$ so that $\tilde{\Gamma}$ is properly defined.

[23] Antràs et al. (2024) present a framework that integrates multinational assembling, sourcing, and exporting decisions and derives conditions for substitutability and complementarity among the firm's assembly plants. Arkolakis et al. (2023) also allows for the firm's plants to be either substitutes or complements.

3.3.2 Optimal Set of Establishment Locations and Technology Adoption

Firms jointly choose optimal communication technology φ and establishment locations S to maximize their total profits, net of the fixed costs of ICT adoption and expansion:

$$\pi_o(z) = \max_{\varphi \in \{\underline{\varphi}, \overline{\varphi}\}} \pi_o(\varphi, z) - \mathbb{1}[\varphi = \overline{\varphi}] f_o^{ICT}(z), \tag{9}$$

where the profit conditional on the technology, $\pi_o(\varphi, z)$, comes from the following location choice problem:

$$\pi_o(\varphi, z) = \max_{S \in \mathscr{S}} \sum_{k=1}^{N} \pi_{ok}(S, \varphi, z) - \sum_{s=1}^{N} \mathbb{1}[s \in S] f_{os}^{X}(z), \tag{10}$$

where $\pi_{ok}(S, \varphi, z)$ is defined as described above for Equation (7). In choosing locations, firms balance benefits from proximity to consumers and potential cost savings, leading to production potential improvements and increased profits, against higher communication costs to headquarters and fixed setup costs. Additionally, the problem shown in Equation (10) is a challenging combinatorial discrete choice problem due to the exponential growth in possible location combinations. To speed up computation, I use the algorithm from Arkolakis et al. (2023), which allows for either substitutability or complementarity among the firm's establishments. Appendix C.4 shows that a sufficient condition, the single crossing differences condition, applies to my setting and outlines the computation algorithm.

3.4 Equilibrium

To fit manufacturing into the entire economy, I assume a nonmanufacturing sector selling homogeneous products that can be traded costlessly across locations. Consumers spend a constant fraction η of final expenditure G_k on manufacturing goods. Labor is freely mobile across the two sectors. The nonmanufacturing sector is large enough that the wage is pinned down by productivity in that sector and total income is exogenous.

Definition: Equilibrium is a vector of prices $\{P_k\}_{k=1}^{N}$ consistent with firm optimization in Equations (7) to (10) and clears the product market for each location. Appendix C.4 provides the detailed equilibrium equations.

Endogenous wages. In Appendix C.4, I further relax the assumption of exogenous wages and total income by assuming a perfectly inelastic labor supply in each location. Appendix F.1 explores how different assumptions on labor supply affect welfare gains in the counterfactual analysis. The reality should fall somewhere between these two cases.

3.5 Technology Adoption and Firm Geography

I illustrate how the adoption of internal communication technology impacts firm geography using a simplified example with three locations: the firm's headquarters (HQ), a nearby location with low productivity and setup costs (L), and a distant, productive location with higher setup costs (H). The firm evaluates the benefits and costs of four location combinations: $\{HQ\}$, $\{HQ, H\}$, $\{HQ, L\}$, and $\{HQ, H, L\}$.

Extensive Margin. Panel A in Figure 4 displays the policy function of the number of establishments against firm fundamental productivity z, along with the set of locations. Compared with the dotted line, the solid line corresponds to better communication technology. More productive firms enter more locations. The set of locations, however, does not monotonically increase in productivity. In the middle range of productivity, less productive firms expand to L, whereas more productive firms expand to H, even if the number of establishments remains the same. By enhancing firm-wide productivity $h(\varphi)$ and reducing internal communication costs $d_{os}(\varphi)$, technology adoption increases the likelihood of firms relocating from L to H and expanding to more locations.

Importantly, the model features complementarity between technological upgrading and geographical expansion; the benefits of expansion are greater for firms that adopt better communication technology, while the benefits of adopting such technology are greater for firms with a larger set of locations. When considering both decisions together, less productive firms maintain low levels of technology and local production, whereas more productive firms adopt better technology and further expand their geographic footprints.

Due to this complementarity, following a reduction in the adoption cost, firms are more likely to adopt better technology, leading to geographic expansion. However, increased efficiency and expansion also result in a more competitive market, which can lead to firm contraction. In equilibrium, the net changes in the firm's geographic span of control depend on the relative strength of these two forces.[24]

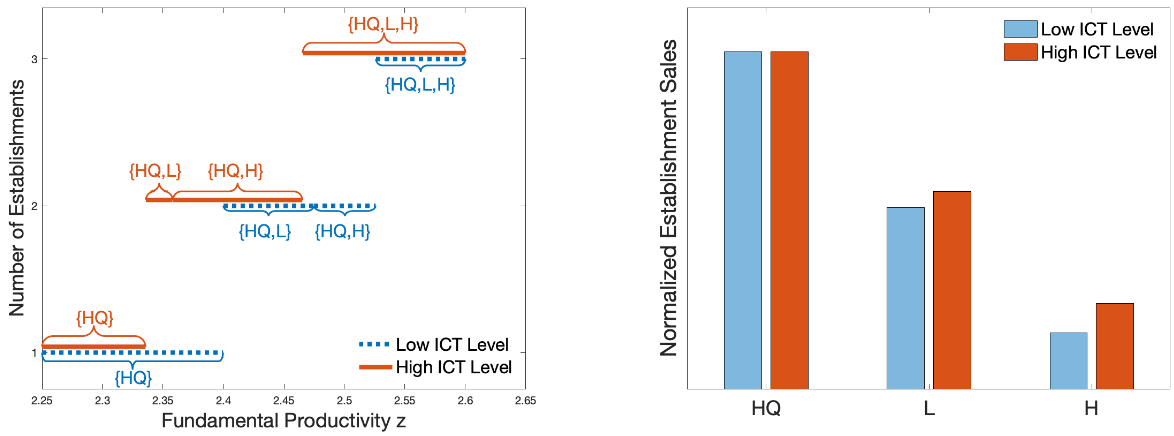
Intensive Margin. The adoption of internal communication technology also affects the within-firm distribution of economic activities across establishments by changing $d_{os}(\varphi)$, even if the firm's location choice remains the same.

Due to the properties of the Fréchet distribution, Appendix C.3 shows that we can write

[24] Appendix C.5 decomposes the equilibrium effects into these two forces in the same three-location example.

Figure 4: ICT and Firm Organization: An Illustration with Three Locations

A. Extensive Margin: Location Choice B. Intensive Margin: Establishment Sales Distribution



Notes: Panel A plots the number of establishments, along with the set of locations, against productivity for a low ICT level (the dotted line) and a high ICT level (the solid line), respectively. Panel B displays the sales of each establishment relative to headquarters' sales for firms operating in all three locations in both low and high ICT levels.

the share of sales to a market k from the firm's establishment $s \in S$ as:

$$\zeta_{ok\leftarrow s}(S,\varphi,z) \equiv \frac{\text{sales}_{ok\leftarrow s}(S,\varphi,z)}{\text{sales}_{ok}(S,\varphi,z)} = \frac{(T_s/w_s)^{\theta}(\tau_{sk}d_{os}(\varphi))^{-\theta}}{\Phi_{ok}(S,\varphi)}. \tag{11}$$

Summing over all markets k, the sales share of an establishment in s, normalized by the sales at the firm's headquarters o, is given by:

$$\log\tilde{\zeta}_{os}(S,\varphi) = -\theta d_{os}(\varphi) + \log\left(\frac{\sum_k \omega_{ok}(S,\varphi)\tau_{sk}^{-\theta}}{\sum_k \omega_{ok}(S,\varphi)\tau_{ok}^{-\theta}}\right) + \theta\log\left(\frac{T_s}{T_o}\right) - \theta\log\left(\frac{w_s}{w_o}\right). \tag{12}$$

The first term on the right-hand side is the communication cost between o and s. The second term represents the normalized establishment's market access, which is a weighted average shipping cost from the establishment to all markets k.[25]

Suppose that $d_{os}(\varphi)$ is log-linear in distance, $d_{os}(\varphi) = e^{\beta^d(\varphi)\log \text{Miles}_{os}}$, and that firms with better communication technology face a smaller elasticity $\beta^d(\varphi)$, meaning that communication costs increase more slowly in distance for those firms. Using the three-location example, Panel B in Figure 4 shows that establishment sales decline as the distance from headquarters increases. However, the decline is less pronounced when firms adopt better technology.As a result, technology adoption leads to firms allocating more sales to nonheadquarters and

[25] In particular, the weight for a market k is $\omega_{ok}(S,\varphi) = \frac{E_k P_k^{\sigma-1}\Phi_{ok}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}}{\sum_{k'} E_{k'} P_{k'}^{\sigma-1}\Phi_{ok'}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}}$, where E_k is the total expenditures in location k, P_k is the local price index, and $\Phi_{ok}(S,\varphi)$ is the production potential.

distant establishments.

In Equation (12), firm-specific components—productivity z and firm-wide communication costs $h(\varphi)$—are canceled out, which allows us to separate the two channels via $h(\varphi)$ and $d_{os}(\varphi)$. In the next section, I use this insight to provide an estimation framework that exploits within-firm labor allocation to quantify the effect of intranet adoption on $d_{os}(\varphi)$.

4 Estimation

The key parameters concern the extent to which the adoption of internal communication technology affects firm-wide productivity $h(\varphi)$ and headquarters–establishment communication costs $d_{os}(\varphi)$. Using the LBD–CNUS matched data, I estimate the model parameters in three steps. In particular, I exploit natural experimental variation from privatization of the Internet backbone of the early 1990s to develop an instrument for firms' technology adoption. In Section 4.1, I describe the parameterization and estimation strategy. In Section 4.2–4.4, I discuss the three steps of estimation.

4.1 Parameterization and Estimation Strategy

I define the location at the census division level. Nevertheless, this operationalization still captures meaningful firm expansion patterns. For manufacturers, the majority of new establishments are in different census divisions from their headquarters. In the following structural estimation, if a firm operates multiple establishments within a census division, I aggregate them into a single large establishment at the census division level.

I assume that firm productivity follows a log-normal distribution with mean μ^z and dispersion σ^z. Trade costs are log-linear in distance, measured in miles, between the production establishment s and the destination market k with elasticity β^τ: $\tau_{sk} = e^{\beta^\tau \log \text{Miles}_{sk}}$.

As one key set of parameters, I assume the headquarters–establishment communication cost $d_{os}(\varphi)$ is log-linear in distance between headquarters o and establishment s.[26] Guided by the empirical results, I use firms' intranet status as a proxy for their internal communication technology in estimation. Importantly, I allow the communication elasticity to vary with firms' intranet adoption: $d_{os}(\varphi) = e^{(\beta_1^d + \beta_2^d \times \text{Intranet}) \times \log \text{Miles}_{os}}$, for $s \neq o$. The communication costs within headquarters are normalized to 1, i.e., $d_{oo}(\varphi) = 1$. The firm-wide communication costs $h(\varphi)$ take two values: $\underline{h}$ for firms without intranets and $\overline{h}$ for those with intranets.

[26] Assuming a log-linear relationship between communication costs and distance is a reduced-form way of modeling obstacles—such as monitoring costs or information leakage risks—that impede communication over long distances.

The fixed costs of adopting an intranet follow a log-normal distribution, with mean μ_o^{ICT} and dispersion σ^{ICT}. As I will discuss in more detail later, I add to the model that locations closer to the Internet backbone nodes face lower adoption costs. Specifically, I assume that μ_o^{ICT} is linear in the log average distance to the nearest backbone node for firms headquartered in census division o: $\mu_o^{ICT} = \beta_1^{ICT} + \beta_2^{ICT} \log(\widetilde{\text{HQDistToNode}}_o)$.

The fixed costs of setting up establishments are also log-normally distributed, with mean μ_{os}^X and dispersion σ^X, where the mean is linear in the log of distance between the headquarters and establishment locations: $\mu_{os}^X = \beta_1^X + \beta_2^X \log(\text{Miles}_{os})$.

Assigned parameters. I assign a set of standard parameters that are held constant for the quantitative analyses, as summarized in Panel A of Table 2. The shape parameter of the Fréchet distributions of the establishment productivity draws is set to $\theta = 3.6$, the medium value used in Eaton and Kortum (2002).[27] I set the within-firm elasticity of substitution $\rho = 4$, while I estimate the cross-firm elasticity of substitution σ, allowing for either complementarity or substitutability among a firm's establishments.

The mean and dispersion of firm productivity are set to $\mu^z = -0.122$ and $\sigma^z = 0.767$, respectively, using the estimates from Guner et al. (2008), who use the 1997 U.S. Census of Manufacturers to estimate the distribution of firm productivity.[28] I set the elasticity of trade costs with respect to distance $\beta^\tau = 0.278$, which implies a conventional trade elasticity of -1 (see Disdier and Head, 2008). Recall that the firm-wide communication cost acts as a shifter for firms' effective productivity; we can identify only the relative magnitude of the two values ($\underline{h}$ and $\overline{h}$). Therefore, I normalize $\overline{h} = 1$.

Estimated parameters. Panel B of Table 2 displays the remaining parameters that I estimate in three steps. In the first step, I estimate the headquarters–establishment communication costs for firms with and without intranets (β_1^d, β_2^d). In the second step, I back out the scale parameters of the Fréchet distribution for establishing productivity at each location ($T_s, s = 1, \cdots, 9$). In the last step, I use the method of simulated moments to jointly estimate the cross-firm demand elasticity (σ), the firm-wide communication cost without an intranet ($\underline{h}$), the distribution of fixed setup costs ($\beta_1^X, \beta_2^X, \sigma^X$), and the distribution of fixed adoption costs ($\beta_1^{ICT}, \beta_2^{ICT}, \sigma^{ICT}$).

[27] Eaton and Kortum (2002) provide three measures of θ, i.e., 2.84, 3.60 and 8.28. Fajgelbaum et al. (2019) estimate θ to be in the range of 2.43 to 2.84 at the state level. Tintelnot (2017) and Hu and Shi (2019) assume that $\theta = 7$ for EU countries. Antras et al. (2017) use the countries from which U.S. firms import and estimate $\theta = 1.789$.

[28] Guner et al. (2008) estimate the distribution of firm productivity, defined as managerial ability, by matching the size distributions of U.S. establishments. They assume that log-managerial ability is normally distributed. The estimated mean is -0.367, and the dispersion is 2.303. Since size is proportional to productivity in Guner et al. (2008) while it is proportional to productivity by a factor of $\sigma - 1$ in my

Table 2: Summary of Parameters

Parameter	Description	Value (S.E)
A. Assigned Parameters		
θ	Dispersion of local productivity	3.6
ρ	Demand elasticity within a firm across varieties	4
μ^z	Mean of log firm productivity (Guner et al., 2008)	-0.123
σ^z	Dispersion of log firm productivity (Guner et al., 2008)	0.767
$\overline{h}$	Firm-wide comm. costs with high ICT	1
β^τ	Elasticity of trade costs w.r.t. distance (Disdier and Head, 2008)	0.278
B. Estimated Parameters		
B.1 Step 1: Estimate within-firm employment share equation		
β_1^d	Elasticity of comm. costs w.r.t distance with low ICT	0.181 (0.055)
β_2^d	ΔElasticity of comm. costs w.r.t distance between low and high ICT	0.109 (0.046)
B.2 Step 2: Decompose location fixed effects		
T	Mean of local productivity for each location	Table E.1
B.3 Step 3: Method of simulated moments		
σ	Demand elasticity across firms	3.285 (0.108)
$\underline{h}$	Firm-wide comm. costs with low ICT	1.385 (0.172)
β_1^X	Intercept of avg. fixed setup costs	2.166 (0.209)
β_2^X	Elasticity of avg. fixed setup costs w.r.t distance	0.141 (0.039)
σ^X	Dispersion of fixed setup costs	2.323 (0.114)
β_1^{ICT}	Intercept of avg. fixed adoption costs of ICT	2.413 (0.736)
β_2^{ICT}	Elasticity of avg. fixed adoption costs of ICT w.r.t. DistToNode	0.102 (0.068)
σ^{ICT}	Dispersion of fixed adoption costs of ICT	3.511 (0.536)

Notes: Panel A displays the assigned parameters. Panel B displays the parameters that are estimated in three steps. Standard errors are reported in the parentheses.

4.2 Estimating Headquarters–Establishment Communication Costs

I first estimate how headquarters–establishment communication costs vary with a firm's intranet adoption. To this end, I exploit within-firm variation in establishment employment shares, taking firm location choices and technology as given.

4.2.1 Estimating Equation

Equation (12) relates the establishment's sales share to the communication costs to its headquarters. By normalizing establishment shares by the headquarters share, factors affecting firm-wide productivity are canceled out, which allows me to isolate the impact of intranets on headquarters–establishment communication costs.

There are a few details worth noting to take Equation (12) to the data. First, sales data were unavailable in the LBD until recently and are at the firm level.[29] Therefore, I

setting, I apply a factor of $1/(\sigma-1)$ to their estimated mean and dispersion to be consistent.

[29] Although the Census of Manufacturers provides sales data every five years, it does not include data

instead use the within-firm *employment shares* for estimation. Appendix E.1 shows that the employment share is analogous to the sales share.

Second, I exploit variation across nonheadquarters establishments by focusing on firms with operations in at least two census divisions outside their headquarters. I examine how the employment shares of these nonheadquarters establishments vary with distance from headquarters.

Third, I approximate the weighted average market access term in Equation (12) by:

$$\log\left(\sum_k \omega_{ok}(S,\varphi)\tau_{sk}^{-\theta}\right) \approx [\phi + \phi_o(S,\varphi)] \underbrace{\log\left(\sum_k \tilde{\omega}_k \tau_{sk}^{-\theta}\right)}_{\equiv \log \overline{MA}_s}. \tag{13}$$

The original weight is given by $\omega_{ok}(S,\varphi) = \frac{E_k P_k^{\sigma-1} \Phi_{ok}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}}{\sum_{k'} E_{k'} P_{k'}^{\sigma-1} \Phi_{ok'}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}}$, where $E_k P_k^{\sigma-1}$ captures the demand from market k and $\Phi_{ok}(S,\varphi)$ is the production potential to that market. The empirical weight is the income share of that market, given by $\tilde{\omega}_k = \frac{N_k \bar{y}_k}{\sum_{k'} N_{k'} \bar{y}_{k'}}$, where N_k is the local population and $\bar{y}_k$ is the local income per capita.

While simplified market access, $\log \overline{MA}_s$, is location-specific, the coefficient $\phi_o(S,\varphi)$ accounts for variations in the original market access term based on headquarters location o, other establishment locations S, and intranet adoption φ. The coefficient ϕ captures the average impact of market access. Given headquarters location o and (S,φ), the correlation between model-derived market access and the linear approximation is 0.97, on average. The high correlation indicates that linear functions of demand-weighted market access approximate the market access term reasonably well.

With the firm's intranet adoption as a proxy for internal communication technology, along with the parameterization of $d_{os}(\varphi)$, Appendix E.1 shows that we can write Equation (12) as

$$\begin{aligned}\log \tilde{\zeta}_{ioS,s} = & -\theta\beta_1^d \log \text{Miles}_{os} - \theta\beta_2^d \log \text{Miles}_{os} \times \text{Intranet}_i \\ & + \phi_{oS1} \log \overline{MA}_s + \phi_{oS2} \log \overline{MA}_s \times \text{Intranet}_i \\ & + \xi_{oS1} + \xi_{oS2} \times \text{Intranet}_i + \xi_s + \varepsilon_{ioS,s}.\end{aligned} \tag{14}$$

All else being equal, the employment share of an establishment changes with the distance to the firm's headquarters, and this elasticity varies with the firm's intranet adoption. ϕ_{oS1} allows differential effects of $\log \overline{MA}_s$ across firms with different headquarters and sets of locations, and ϕ_{oS2} further allows those effects to differ between firms with and without in-

for 1999, i.e., the year for which we have adoption data.

tranets. $(\xi_{oS1} + \xi_{oS2} \times \text{Intranet}_i)$ are fixed effects for different headquarters–set combinations, which also vary by a firm's intranet adoption. Despite the large number of possible combinations, we can control for these fixed effects. When each firm has a unique combination of headquarters and a set of locations, they are equivalent to firm fixed effects. ξ_s are establishment location fixed effects.[30] $\varepsilon_{ioS,s}$ is an error term that captures firm-establishment-specific shocks, or measurement errors. I also include industry fixed effects.

In Equation (14), if establishments indeed become smaller the farther they are from headquarters, the coefficient of $\log \text{Miles}_{os}$ would be negative. Moreover, the coefficient of the interaction term $(-\theta\beta_2^d)$ is crucial: a positive coefficient would suggest that establishments belonging to firms with intranets experience a slower decline in size, as the model implies. This regression not only tests the model, but also estimates the second channel through which intranet adoption improves internal communication.

Here, I assume that the firm's location choice does not depend on the error term. This assumption would hold if firms learn their establishment-specific shocks after choosing their locations. One might also be concerned that firms selecting into intranet adoption might be systematically different. For example, firms with large establishments in distant locations may be more likely to adopt better technologies, leading to an upward bias. To address this concern, I supplement the OLS regression with an instrumental variable approach that I outline below.

4.2.2 Instrumental Variable from the Internet Privatization

The instrumental variable approach exploits natural experimental variation in the cost reduction of adopting intranets from a milestone in early U.S. Internet history—the Internet privatization. This event also enables me to test a key model implication regarding firms' geographic expansion following reductions in technology adoption costs.

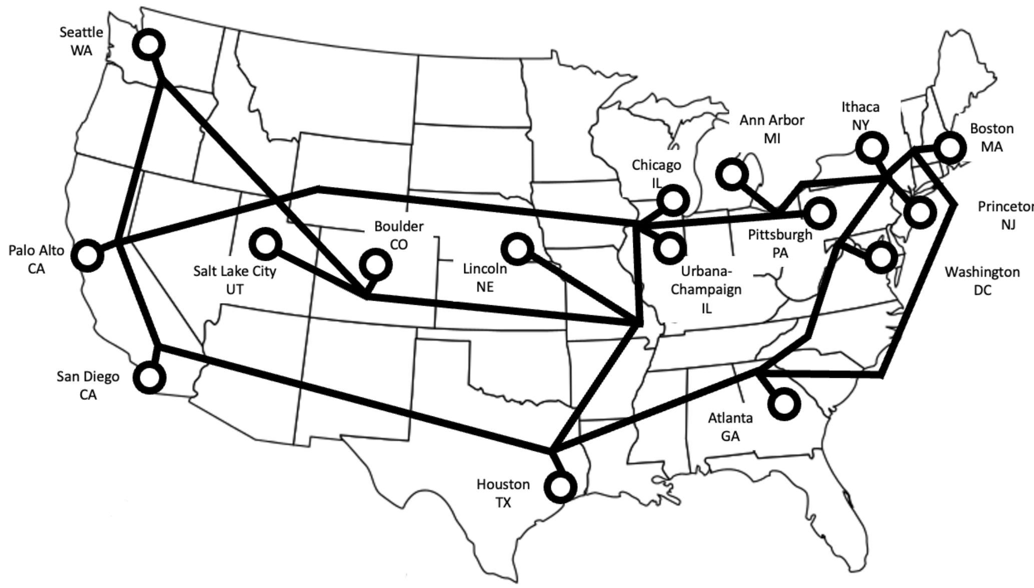
I summarize this event below. Appendix D.1 provides more details.

Internet privatization. The first high-speed Internet backbone in the U.S., namely, NSFNET, was launched in 1986 and was operated by the government through the NSF. By the early 1990s, NSFNET connected sixteen node sites across the U.S., as shown in Figure 5, reflecting historical factors related to proximity to military bases and university locations.[31] Each node was in turn connected to a regional network.

[30]Specifically, $\xi_s = \theta \log T_s - (\theta + 1) \log w_s + \phi \log \overline{MA}_s$, which summarizes the establishment location's state of technology, wage costs, and average market access.

[31]Several NSFNET node locations were inherited from the Advanced Research Projects Agency Network (ARPANET), which was NSFNET's predecessor as a military-funded Internet backbone run by the Department of Defense.

Figure 5: Map of NSFNET in 1992



Notes: This figure shows the NSFNET backbones and its node sites in 1992. The circles represent the exterior nodes. The black lines represent traffic flows on the network.

NSFNET was originally designed for use by the research and higher education community; thus, businesses were generally not allowed to connect to NSFNET to carry their data. With exploding commercial demand, however, these restrictions were gradually lifted. Eventually, in the early 1990s, the Internet—once a government asset—was handed over to the private sector. The privatization was finalized on April 30th, 1995, followed by the so-called Internet gold rush.[32] Appendix Figure C.1 shows a surge in the number of Internet service providers advertised in a national magazine since then.[33]

To measure the firm's exposure to the privatization of NSFNET, I use the distance from a firm's headquarters to the nearest NSFNET node site. Locations closer to these nodes had better infrastructure, such as underground fiber optic lines. As businesses often access the Internet through leased lines and the construction and installation of circuits is a major cost for Internet service providers, the costs of Internet access for businesses are lower if they are in locations with better infrastructure.[34] In the following reduced-form analysis, I

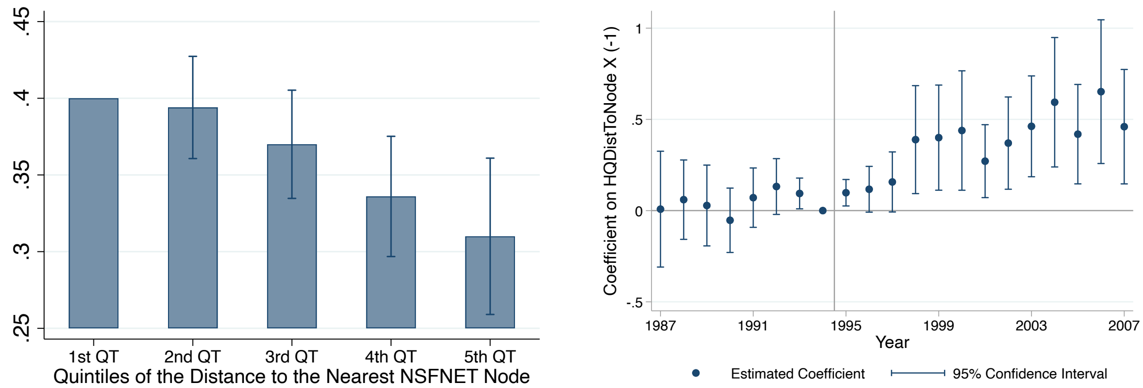
[32]The conversation concerning the privatization of the Internet started in the early 1990s, and commercial businesses were allowed to connect to the Internet around 1992. Nevertheless, the final privatization of the Internet that occurred in 1995 served as a catalyst for the Internet gold rush.

[33]This figure is made from Table 5.1 in Greenstein (2015). The slow-growing number of Internet service providers before 1995 and the market explosion shortly after 1995 reflect the critical role of the Internet privatization.

[34]McKnight and Bailey (1998) document that costs for leased lines and routers accounted for 80% of total NSFNET costs. Bloom et al. (2014) use country-level variations in the leasing of telephone lines to instrument for firms' probability of adopting an intranet; they use the distance to the headquarters of SAP

Figure 6: Distance to NSFNET Nodes and Internet Privatization

A. First-Stage Evidence B. Reduced-Form Effects



Notes: Panel A shows the share of firms adopting intranets for each quintile of distance to the nearest NSFNET node, controlling for county characteristics, industry and state fixed effects. Panel B shows the regression coefficients in Equation (15). The regression is weighted by firms' employment share. Standard errors are clustered at the firm and county level.

measure the distance at the zip code level, whereas the structural estimation is consistently conducted using measures at the census division level.

Using firms' intranet adoption in the 1999 CNUS data, Panel A in Figure 6 shows that firms located closer to nodes were more likely to have adopted an intranet in 1999 after the Internet privatization. To ensure that locations and firms are comparable along the distance, I control for county characteristics and include both industry and state fixed effects. The negative relationship indicates that the distance measure can capture heterogeneity in the effect of the Internet privatization on intranet adoption.

Reduced-form evidence. Before constructing the instrument for intranet adoption, I present reduced-form evidence to test a key model implication on the extensive margin: cost reduction in adopting communication technology leads to firms' geographic expansion.

My empirical approach builds on the idea that following the Internet privatization, firms located closer to Internet backbone nodes experienced a larger cost reduction in accessing high-speed Internet and thus advanced business applications, such as intranets.

The reduced-form takes the form of a difference-in-differences regression framework:

$$Y_{it} = \alpha_i + \beta_t \text{HQDistToNode}_i + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it}, \tag{15}$$

where Y_{it} is a measure of the geographic span of control of firm i in year t. I use the number of establishments as the main measure, while the results are robust to other measures, such

to measure firms' probability of adopting ERP software. Forman et al. (2012) use county-level variation in the number of nodes for ARPANET as an instrument for local advanced IT investment by businesses.

as the number of census divisions. α_i is firm fixed effects. HQDistToNode_i is the distance (in hundreds of miles) of the ZIP code in which firm i is headquartered to the nearest NSFNET node. The coefficient of interest, β_t, measures whether the firms headquartered closer to nodes display different preprivatization trends from firms far away from the nodes, and how their geographic span of control is affected by privatization. I include industry–year and state–year fixed effects, where industry is at the 4-digit NAICS level. In some specifications, I also control for county–year-specific characteristics, including the log population and median household income, the shares of the Black population and of people over 65 years old, and the share of adults with bachelor's degrees. Standard errors are clustered at the firm and county levels.[35]

Local infrastructure might affect firms' headquarters locations. To eliminate this concern and abstract from firm entry and exit, I focus on a balanced panel of about 33,500 firms from the LBD spanning 1987 to 2007 for the reduced-form analysis. Table A.3 reports the summary statistics of the balanced sample.

The identification assumption is that the Internet privatization did not coincide with other location-by-year shocks. To validate this assumption, I present graphical evidence that firms display similar trends in their geographic scope before privatization, regardless of proximity to the backbone nodes. Panel B in Figure 6 shows the estimated coefficients β_t and 95% confidence intervals. For easier presentation, I normalize the coefficients by the estimate in 1994, i.e., $\beta_t - \beta_{1994}$, and multiply them by -1. I find no evidence of pre-trends. For years from 1995 onward, the estimated coefficients are negative (positive after multiplied by -1 in the graph), indicating that firms located *closer* to NSFNET nodes had *more* establishments. The gradual increase after privatization may reflect the time needed to integrate ICT systems into firm operations or set up new establishments. The estimates are statistically significant at the 5% level and stable over the 2000s, suggesting that the benefits for firms close to nodes were long-lasting, e.g., due to the constant arrival of new technologies or initial competitive advantages for firms expanding at an early stage.

To quantify the impact of the Internet privatization on firms' geographic span of control, Table 3 reports the estimates of the following difference-in-differences regression:

$$Y_{it} = \alpha_i + \beta \text{HQDistToNode}_i \times \text{Post}_t + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it}, \tag{16}$$

where Post_t is an indicator set to one for years from 1995 onward. Regressions are weighted by firm employment.

One may be concerned that firms and locations located closer to NSFNET nodes are

[35] In a robustness check, I cluster the standard errors at the firm and state levels.

different from those located far away. To address this issue, I construct generalized propensity scores, conditional on firm and county characteristics before privatization, and apply the inverse propensity score (IPW) method to reweight the observations. Figure C.2 shows that after the propensity score reweighting, firm and county characteristics are balanced along the distance.[36]

Column (1) of Panel A estimates β at -0.328, indicating that firms located 100 miles *closer* to a node are associated with 0.328 *more* establishments after privatization. As the average distance is approximately 130 miles, the Internet privatization increased firms' geographic span of control, on average, by 0.426 ($= 0.328 \times 130/100$) establishments. Given the average of 5.016 establishments per firm, this translates into a 8.5% ($= 0.426/5.016 \times 100$) increase. Columns (2)–(5) show that the estimated effect is robust to (i) including time-varying county characteristics, (ii) restricting to multi-unit firms, (iii) using equal weights, i.e., unweighted regression, and (iv) using the inverse propensity score method. Particularly, the IPW result in Column (5) reports a reweighted difference-in-differences estimate of 0.065. This estimate translates into a 7.2% increase in the firm's number of establishments, similar to the 8.5% increase from the baseline regression. Overall, these results convince us that local shocks or firms' initial selection into different locations are unlikely to drive the baseline estimate.

Panel B of Table 3 confirms that the increasing number of establishments per firm reflects wider geographic coverage of the firm. Columns (1)–(3) show that privatization increased firms' geographic scope by 7% at the county level, 5.5% at the state level, and 2.6% at the census division level. Columns (4)–(5) also consider the number of establishments outside the headquarters state and at a nondrivable distance from the headquarters.

Appendix Table D.4 categorizes industries on the basis of their average shipping distance, with the idea that a shorter shipping distance implies higher shipping costs. Consistent with the model, the effect is stronger for industries with high shipping costs, whereas it is smaller and statistically insignificant for industries with low shipping costs.

Appendix Table D.3 shows that firms headquartered *closer* to nodes also build new establishments *closer* to the nodes. This is consistent with our premise that interlocutors at both ends of the communication channel need access to the technology.

Finally, Appendix Table D.1 shows that the estimated effect is robust to excluding firms close to the nodes that are university towns and to alternative clustering of the standard errors. Appendix Table D.2 presents additional results regarding firms' employment.

In sum, the reduced-form evidence shows that firms expand geographically following a

[36] Appendix D.2.1 provides more details on how I construct the generalized propensity scores of treatment (see Robins et al., 2000; Hirano and Imbens, 2004; Abadie, 2005).

Table 3: Estimated Effects of Internet Privatization on Firms' Geographic Expansion

A. Number of Establishments per Firm	Baseline (1)	County Controls (2)	Multi-unit Firms (3)	Unweighted (4)	IPW (5)
HQDistToNode × Post	-0.328***	-0.323***	-0.442**	-0.044**	-0.065***
	(0.098)	(0.097)	(0.191)	(0.017)	(0.023)
N	702000	702000	34500	702000	702000
Avg. Dep. Var	5.016	5.016	8.841	1.340	1.179
R^2	0.899	0.899	0.897	0.865	0.915
County controls		Y	Y	Y	Y
Industry-Year	Y	Y	Y	Y	Y
State-Year	Y	Y	Y	Y	Y

B. Alternative Measures of Firms' Geographic Span of Control

Number of	Counties (1)	States (2)	Census Divisions (3)	Out-of-State Estabs. (4)	Non-Drivable Estabs. (5)
HQDistToNode×Post	-0.249***	-0.144***	-0.048**	-0.326***	-0.321***
	(0.082)	(0.044)	(0.019)	(0.092)	(0.090)
N	702000	702000	702000	702000	702000
Avg. Dep. Var	4.587	3.406	2.439	3.777	3.327
R^2	0.916	0.928	0.921	0.896	0.887
County controls	Y	Y	Y	Y	Y
Industry-Year	Y	Y	Y	Y	Y
State-Year	Y	Y	Y	Y	Y

Notes: This table uses the manufacturing firms in the LBD from 1987 to 2007 and estimates regression (16). The dependent variable in Panel A is the number of establishments a firm operates. In Panel B, the dependent variables for Columns (1)–(3) are the number of counties, states, and census divisions where the firm has establishments. The dependent variable for Columns (4)–(5) are the firm's number of establishments that are out of the headquarters state and that are nondrivable from the headquarters, i.e., over 250 miles away from the headquarters. Standard errors are clustered at the firm and headquarters county level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

large reduction in adoption costs, thereby validating a key model implication on the extensive margin.

Instrumental Variable. Now, I construct an instrument for firms' intranet adoption using the plausibly exogenous variation from the Internet privatization. Ideally, I would like to have a panel that records firms' intranet adoption status before and after the Internet privatization. Unfortunately, this type of panel data is not available. Nevertheless, as Internet-based intranets were first commercialized in 1996, after the Internet privatization, I create a time-varying indicator of a firm's intranet status by interacting the firm's intranet adoption in 1999 with a postprivatization indicator, i.e., $\text{Intranet}_{it} = \text{Intranet}_i \times \text{Post}_t$ for firm i in year t. I merge in the firm's intranet adoption from the CNUS data to the sample that runs Equation (16) and restrict to years up to 1999 to minimize the scope of measurement errors resulting from the construction of my time-varying intranet variable.[37]

[37]As the firms in the matched sample are, on average, larger and more likely to be multi-unit firms

The first-stage regression takes the same form as Equation (16) but replaces the dependent variable with the firm's intranet adoption:

$$\text{Intranet}_{it} = \alpha_i + \beta \text{HQDistToNode}_i \times \text{Post}_t + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it}. \qquad (17)$$

Column (1) of Table D.5 shows that firms that are located 100 miles closer to a node are associated with a 3.5 percentage point higher probability of adopting an intranet, more than doubling the likelihood on average (= 0.035 × 130/0.036). The exclusion restriction requires that the instrument affects within-firm allocation across establishments only through their intranet adoption. I therefore test whether other online advanced applications affect the outcome. I follow the same procedure as that used to build the Intranet measure, construct indicators for adoption of other networks, and compare the first-stage estimates using these variables as outcomes. Columns (2)–(4) show that the estimated coefficients on other network adoptions are either smaller than that on Intranet or statistically insignificant. A longer distance to the node even predicts a greater likelihood of adopting the Internet, reflecting the fact that adoption of the basic Internet had reached saturation by the end of the 1990s. These results provide reassurance that the firm's intranet adoption is the major channel through which the Internet privatization, particularly HQDistToNode_{it}, affects firms intranet adoption.

Finally, I use the predicted probability of intranet adoption of a firm i in 1999 from Equation (17), i.e., $\widehat{\text{Intranet}}_{i,99}$, as an instrument for Intranet_i in the structural estimation equation (14) and interactions between the predicted probability and other variables, e.g., $\log \text{Miles}_{os} \times \widehat{\text{Intranet}}_{i,99}$ as instruments for the corresponding interaction terms.

4.2.3 Estimation Results

I estimate Equation (14) using the firms and their establishments in the LBD–CNUS matched sample. Table 4 shows the results. Columns (1)–(2) abstract away from technology adoption, serving as a first pass for the relationship between establishment employment shares and distances to headquarters. Column (1) covers observations throughout the 1987–2007 period. The estimated coefficient on Log(Miles) is −0.172, indicating that a 10% increase in the distance leads to a 1.7% reduction in the establishment's employment share.Columns (2)–(4) use observations for 1999, the year for which we have firms' intranet adoption information.

In the baseline regression in Column (3), I add the intranet adoption variable. While the coefficient on Log(Miles) is still negative, the coefficient on the interaction of Log(Miles)

than firms in the baseline sample for the above reduced-form analysis, I estimate the conditional probability of a firm belonging to the matched sample, i.e., the propensity score, and then apply the inverse propensity scores to reweight the matched subsample (see Chen et al., 2008).

and Intranet is positive, confirming that the elasticity is *smaller* for firms with an intranet. As I calibrate θ to 3.6, the elasticity of communication costs with respect to the distance for firms without an intranet is $\beta^d_{\text{Low ICT}} = 0.181 = (0.652/3.6)$; that for firms with an intranet is $\beta^d_{\text{High ICT}} = 0.072 = ((0.652 - 0.394)/3.6)$, which is less than half that for the former. The instrumental variable approach in Column (4) confirms this finding, with an even larger difference in elasticity between firms with and without intranets.[38] One reason for the larger effect from the 2SLS estimates may be that given the same geographic footprints, firms initially subject to poor communication between headquarters and establishments are more incentivized to adopt an intranet.

I interpret the coefficients on the distance between headquarters and establishments as communication costs rather than physical shipping costs. Atalay et al. (2014) use the Commodity Flow Survey (CFS) and find little interplant shipping even within vertically integrated firms. Additionally, I focus on the firm's within-industry expansion, which limits the scope for shipping intermediate inputs within the firm.[39]

To summarize, the first-step regression yields estimates of the elasticity of within-firm communication costs $d_{os}(\varphi)$ and quantifies the impact of an intranet on this elasticity, which is one of the two sources of firm efficiency improvements.

4.3 Estimating Local Productivity

The first-step regression in Column (1) of Table 4 delivers a vector of fixed effect estimates for each census division s and year t, $\hat{\xi}_{st}$. Drawing on the model structure, Appendix E.1 shows that these fixed effects can be written as

$$\xi_{st} = \underbrace{\theta \log T_{st}}_{\text{local productivity}} - (\theta + 1) \underbrace{\log w_{st}}_{\text{wages}} + \phi \underbrace{\log \overline{MA}_{st}}_{\text{market access}} . \tag{18}$$

In the second step, I decompose the estimated fixed effects to back out T_s, scale parameters of location-specific Fréchet distributions, which represent the average local productivity.

I first construct "purified" location fixed effects that are purged of the wage component by appealing to the calibrated value of θ: $\tilde{\xi}_{st} \equiv \hat{\xi}_{st} + (\theta + 1) \log w_{st}$, where w_{st} is the education-adjusted average weekly wage of the manufacturing sector.[40]

[38] The instrument has reasonably well predictive power, with a first-stage F statistics of 15.27. The estimated coefficients show $\beta^d_{\text{Low ICT}} = 0.334$ and $\beta^d_{\text{High ICT}} = 0.057$, reflecting an over 80% reduction in communication costs. Standard errors are calculated by 1,000 bootstrapped samples to account for both the first- and second-stage regressions.

[39] Keller and Yeaple (2013) presents a model in which multinationals can transfer knowledge embodied in intermediates, explaining the observed decrease in affiliate sales with increasing distance.

[40] The education-adjusted wage is calculated by $w^{\text{adj}}_{st} = w_{st} \exp(\mu H_{st})$, where H_{st} is the average years

Table 4: First-Step Estimation Results

Dependent Variable:	All Years	Year 1999		
Establishment Employment Share	OLS	OLS	OLS	IV
	(1)	(2)	(3)	(4)
Log(Miles)	-0.172***	-0.293**	-0.652**	-1.202***
	(0.047)	(0.137)	(0.199)	(0.387)
Log(Miles) × Intranet			0.394**	0.997**
			(0.167)	(0.401)
N	59500	3100	3100	3100
F-stat				15.27
Market Access	Y	Y	Y	Y
HQ-Set-ICT FE	Y	Y	Y	Y
Establishment Location FE		Y	Y	Y
Industry FE		Y	Y	Y
Establishment Location-Year FE	Y			
Industry-Year FE	Y			

Notes: This table estimates regression (14). The dependent variable is the scaled within-firm employment shares of establishments. Log(Miles) is the distance between the firm's headquarters and the establishment. As a control, the Market Access term includes the full interactions of the simplified market access term with the HQ-Set-ICT triplet. Standard errors are clustered at the firm level. Standard errors in Column (4) are calculated by 1,000 bootstrapped samples. Regressions are weighted by the weights provided in the 1999 ASM. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

To estimate the coefficient ϕ, I follow the convention by approximating local productivity by local R&D stocks and estimate the following regression:

$$\tilde{\xi}_{st} = b_0 + b_{RD} \log \text{R\&D}_{st} + \phi \log \overline{MA}_{st} + \gamma_t + \delta_s + u_{st}, \tag{19}$$

where $\tilde{\xi}_{st}$ is the purified location fixed effects anad where $\log \text{R\&D}_{st}$ and $\log \overline{MA}_{st}$ are the logarithms of the local R&D stock and local market access, respectively.[41] γ_t is year fixed effect. δ_s is the census division fixed effect.

Table 5 shows the estimated coefficients. Columns (1) and (2) control for R&D stock and market access, respectively, whereas Column (3) includes both terms. Consistent with the premise that the location's appeal increases with local productivity and market access, the coefficients on both terms are positive and statistically significant. As the baseline specification in Column (3), ϕ is estimated at 0.743. Given this estimate, I construct T_{st} by

of schooling in census division s and year t, and μ is the return to schooling set to 0.06 following Bils and Klenow (2000). Columns (1) and (2) in Table E.1 report the raw and purified fixed effects, respectively, for each census division in 1999, normalized by the New England census division.

[41] I construct local R&D stocks by the perpetual inventory method, using state-level industrial R&D expenditure from the Survey of Industrial Research and Development. Before 1998, the R&D expenditure data were published only for odd years. Following Wilson (2009), I interpolate the data by averaging the values for the years before and after. Then, I calculate the R&D stock by $\text{R\&D}_t^{\text{stock}} = (1 - \delta_{\text{R\&D}})\text{R\&D}_{t-1}^{\text{stock}} + \text{R\&D}_t^{\text{exp}}$, where the depreciation rate is set to 0.15.

Table 5: Second-Step Regression Results

	Purified Estimates of Census Division FEs		
	(1)	(2)	(3)
Log(R&D stock)	0.741***		0.635***
	(0.126)		(0.106)
Log(Market access)		0.887***	0.743**
		(0.255)	(0.225)
N	189	189	189
R^2	0.966	0.965	0.972
Census Division FE	Y	Y	Y
Year FE	Y	Y	Y

Notes: This table estimates the regression in Equation (19). The dependent variable is the census division fixed effect from 1987 to 2007 estimated in the first-stage regression and purged of local wages. R&D stocks are constructed by the perpetual inventory method using industrial R&D expenditure at the state level and aggregated to the census division level. Market access is approximated by the average trade cost weighted by demand from each destination market. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

$\log(T_{st}) = (\tilde{\xi}_{st} - \hat{\phi} \log \overline{MA}_{st})/\theta$, reported in Column (3) of Table E.1.

4.4 Method of Simulated Moments

In the third step, I use the method of simulated moments to jointly estimate (i) demand elasticity across firms σ; (ii) the firm-wide communication cost for low communication technology $\underline{h}$, which captures the other channel of the technology impacts; (iii) the mean and dispersion of fixed costs of geographic expansion $(\beta_1^X, \beta_2^X, \sigma^X)$; and (iv) the mean and dispersion of fixed adoption costs $(\beta_1^{ICT}, \beta_2^{ICT}, \sigma^{ICT})$.

The parameter vector is denoted as $\psi = \{\sigma, \underline{h}, \beta_1^X, \beta_2^X, \sigma^X, \beta_1^{ICT}, \beta_2^{ICT}, \sigma^{ICT}\}$, the data moments as m, and the simulated moments as $\hat{m}(\psi)$. The estimate $\hat{\psi}$ minimizes the criterion function:

$$g(\psi) = [m - \hat{m}(\psi)]' W [m - \hat{m}(\psi)], \tag{20}$$

where W is the weighting matrix. I use the identity matrix as a weighting matrix ($W = I$).

Simulation. For each location, I simulate 10,000 firms headquartered there. Although the number of simulated firms is the same in each location, the mass of firms varies across locations. I calculate the firm mass using the number of firms observed in each location from the LBD. Each firm draws a productivity z, a fixed cost of technology adoption f_o^{ICT}, and a vector of fixed setup costs in each location f_{os}^X, given the firm's headquarters o. f_{oo}^X is set to zero. Given these shocks, firms choose a set of locations and decide whether to adopt ICT. For each ICT level, the location decision involves a combinatorial discrete choice problem, where I adopt the algorithm proposed by Arkolakis et al. (2023) to expedite computation.

Moments and identification. Table 6 summarizes the targeted moments.

(i) The first set of moments informs us about the fixed costs of expansion. The overall share of multi-unit firms pins down the mean of the fixed setup costs β_1^X. The share of multi-unit firms with employment below the median helps identify the dispersion of fixed costs σ^X. If there was no dispersion, only the most productive firms, which are also the largest firms, would become multi-unit. As these fixed costs become more dispersed, firms with low productivity may draw small fixed costs, allowing them to expand. The correlation between the share of firms headquartered in o and expanded to $s \neq o$ (i.e., Share of firms_{os}) and the log miles between the two census divisions identifies the role of distance in the fixed costs β_2^X.

(ii) Similarly, the second set of moments identifies the mean and dispersion of the fixed costs of intranet adoption. In particular, the role of distance to NSFNET nodes, β_2^{ICT}, is pinned down by the correlation between a firm's intranet adoption and the log average distance to the nearest node from the firm's headquarters.[42]

(iii) The correlation between a firm's intranet adoption and its multi-unit status identifies the firm-wide communication cost without an intranet $\underline{h}$. The higher the correlation is, the greater the difference between firms with and without intranets is.

(iv) The sales share of the top 1% of firms pins down the cross-firm demand elasticity σ. A higher value of σ means that consumers are more price sensitive, allowing firms with lower prices to capture a larger market share. Importantly, this parameter also governs the complementarity or substitutability among a firm's establishments. If $\sigma - 1 < \theta (> \theta)$, then establishments are substitutes (complements); thus, adding one reduces (increases) the sales of others despite the firm's overall sales increasing.

Estimation results. The last panel in Table 2 reports the third-step estimation results.[43] The estimated demand elasticity across firms σ is 3.285, which is smaller than $\theta+1$, suggesting that a firm's establishments are substitutes. While adopting an intranet allows firms to expand to more locations and increases the overall sales of the firm, sales at their existing

[42]To account for geographic area differences at the census division level, I normalize the average distance in each census division by its land area; that is, $\widetilde{\text{HQDistToNode}}_o = \overline{\text{HQDistToNode}}_o / \text{LandArea}_o$. As the distance measure is a proxy of ICT accessibility, the scaled term measures the density of ICT accessibility per square mile. The normalization captures the fact that for larger areas, it is harder for an average firm to reach any node.

[43]Figure C.3 plots the loss function against each parameter with the other parameters held at their estimated values, confirming that the estimates minimize the criterion function.

establishments decline. $\underline{h}$ is estimated to be 1.385, indicating that intranet adoption enhances firm productivity by approximately 30%(= $\log 1.385 - \log 1$).

The fixed setup cost f_{os}^X increases with distance, with an elasticity of 0.141. Column (1) in Table E.2 displays the monetary value of average fixed costs paid by firms expanding to each census division, ranging from \$3.53 million in the New England to \$6.69 million in the South Atlantic.[44] Through the lens of the model, these costs are approximately 18% of total firm profits, on average. As the model does not distinguish between the sunk cost of setting up an establishment versus the flow cost paid to maintain remote establishments, the estimates could include both types of costs.

Compared with f_{os}^X, the fixed costs of intranet adoption are lower, as shown in Column (2) of Table E.2. The average costs paid by adopters range from \$1.97 million in the Mountain to \$2.29 million in the Middle Atlantic. These costs may include not only monetary expenses for purchasing hardware and software but also forgone profits due to the time spent upgrading the system. The fixed costs increase in the location's average distance to the nearest NSFNET node, which measures local technology access, with an elasticity of 0.102. As many small and single-unit firms also adopt an intranet in the data, there is large dispersion in the adoption costs.

Model fit. The last column in Table 6 shows that the model is able to replicate the data moments well. To further validate the model, I compare the simulated bilateral expansion patterns—the share of firms that are headquartered in the census division o and have establishments in the census division s—to those shares from the data. The correlation between the model-simulated and actual expansion patterns is approximately 0.774, underscoring that the model does a good job in matching both the targeted and untargeted moments.

5 Efficiency Gains from Communication Technology and Policy Implications

Using the estimated model, I quantify the efficiency gains from policies aimed at reducing costs of adopting communication technology. I start by analyzing the Internet privatization in Section 4.2.2, representing one of the largest government ICT infrastructure projects in U.S. history, and I clarify the underlying mechanisms that drive efficiency gains across locations. I then discuss the implications for policies improving ICT access and reducing the digital divide.

[44] I calculate the costs by assuming that the ratio of average sales to the fixed costs from the model is the same as that in the data. Costs are measured in 1999 US dollars.

Table 6: Data and Model-Simulated Moments

Moment	Data	Model
Share of multi-unit firms	0.343	0.342
Share of multi-unit firms with emp. below median	0.020	0.025
Corr(Share of firms$_{os}$, Log(Miles$_{os}$))	-0.369	-0.369
Share of firms adopting intranets	0.367	0.362
Share of firms adopting intranets with emp. below median	0.048	0.065
Corr(Intranet, Log($\widetilde{\text{HQDistToNode}}_o$))	-0.028	-0.025
Corr(Intranet, Multi-Unit)	0.555	0.559
Sales share of top 1 percent firms	0.421	0.422

Notes: This table compares the model simulated moments to data moments.

Multi-unit firms and their endogenous location choices are crucial in shaping the geographic distribution of the efficiency gains from these policies.

5.1 Efficiency Gains from Internet Privatization

To simulate the 1995 Internet privatization, I change the fixed costs of technology adoption to match my reduced-form estimate of a 2.56% increase in the average number of census divisions, as reported in Column (3) in Panel B of Table 3.[45] Since the model is estimated to match moments in 1999, the fixed costs of adoption are estimated for the postprivatization economy. To back out prereform fixed costs using the reduced-form estimate, I use the partial equilibrium version of the model, fix the equilibrium prices, and increase the average distance to NSFNET nodes in the fixed costs.[46] The other parameters are held constant. The fixed costs are set to be 65% higher before Internet privatization to match the 2.56% reduced-form change, as shown in Columns (1)–(2) of Table 7.

Given the associated prereform costs, I simulate the full model, allowing equilibrium prices to adjust accordingly. Column (3) of Table 7 shows that due to tougher market competition, the general equilibrium effect on firms' geographic expansion is smaller than that in partial equilibrium.

The second row shows that the Internet privatization increases efficiency by approximately 1.7% at the national level.[47] Panel A in Figure 7 further displays the efficiency gains

[45]The estimated coefficient on the interaction term HQDistToNode × Post is −0.048. Considering that the average distance to a node is 130 miles and that the average dependent variable is 2.439, we can translate the estimate into a 2.56% increase in the average census division per firm (= 0.048 × 130/100/2.439 × 100%).

[46]The difference-in-differences regression shown in Equation (16) controls for state–year fixed effects. These fixed effects help to eliminate the equilibrium effects of price changes since prices are determined at a more aggregate level than states, such as census divisions.

[47]I calculate aggregate efficiency gains by taking the average of local efficiency gains across locations,

Table 7: Simulating Internet Privatization

%Change in	Reduced Form (1)	Model: Partial Equilibrium (2)	Model: General Equilibrium (3)
Number of census divisions per firm	2.56	2.56	1.52
National efficiency			1.69
National welfare with endogenous wages			1.80

Notes: This table shows the changes in firm geographic span of control and efficiency from the Internet privatization. Column (1) reports the reduced-form estimate. Column (2) shows the simulated changes with fixed prices. Column (3) shows the simulated changes in the baseline model with endogenous prices.

in each census division, measured by changes in the inverse of local price indices, ranging from 1.46% in the West South Central to 1.79% in the Pacific. Given a 65% decrease in the cost of adopting communication technology, these estimates indicate an elasticity of efficiency with respect to the cost of adoption between 0.022 and 0.028.

Magnitude. It is worth discussing the magnitude of the efficiency gains before we examine the main mechanisms behind these estimates. The Bureau of Labor Statistics has reported a 20.7% increase in manufacturing labor productivity from 1996 to 2000.[48] This implies that the estimated efficiency gains account for approximately 8 percent of this overall post-1995 productivity growth. While the literature has extensively documented the positive relationship between ICT investment and firm production efficiency, there is no consensus on the sources of these efficiency gains.[49] Here, I propose a new source of efficiency gains from ICT, particularly internal communication technology, by allowing firms to expand geographically. By discipline the effects of communication technology using micro data on the relationship between firms' geographic operations and their technology adoption, I find nontrivial efficiency gains that are greater than what would be achieved without considering firms' geographic expansion.

Endogenous wages. Appendix F.1 extends the baseline model by incorporating an inelastic labor supply in each location, allowing wages to adjust accordingly. The overall gain in welfare, which is measured by the ratio of wages to the local price index, is slightly greater at 1.8%. Table F.1 breaks down the welfare change to changes in efficiency, which is approximately 1.76%, and in wages, which is approximately 5%. Concerning wages, two opposing

weighted by each location's consumption share.

[48]The BLS has reported quarterly labor productivity for major industries: `https://www.bls.gov/productivity/tables/labor-productivity-major-sectors.xlsx`.

[49]Jorgenson et al. (2008) and Van Reenen et al. (2010) use aggregate data and large-scale firm-level datasets from multiple countries, respectively, and find that ICT investment and usage played crucial roles in driving post-1995 aggregate productivity growth in the U.S.

forces come into play as more firms opt for adoption. On the one hand, price indices decline, driving up output demand and consequently labor demand. On the other hand, the unit labor requirement for production decreases, which reduces labor demand. On average, wages increase as the former channel dominates. However, while most regions experience wage increases, the East South Central and West South Central census divisions decrease, driven by declines in the unit labor requirement as local establishments become more productive.

5.1.1 Mechanisms

The aggregate and geographic distribution of efficiency gains are driven by three main mechanisms. First, firms can expand geographically by adopting better technologies, because of the reduced adoption costs. Second, better technology reduces headquarters—establishment communication costs $d_{os}(\varphi)$. Third, better technology also reduces firm-wide communication costs $h(\varphi)$, leading to an improvement in firm effective productivity.

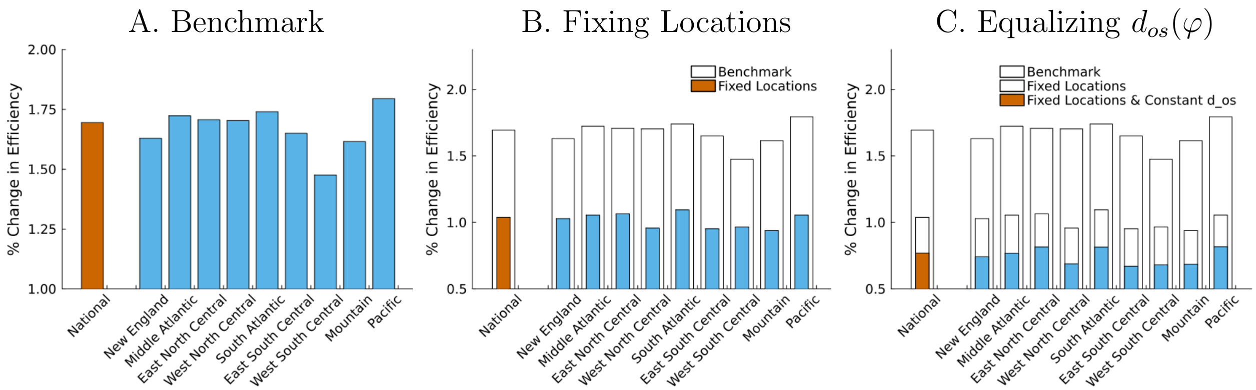
I use the model to quantify the contribution of each mechanism. To that end, I first compute a counterfactual that shuts down firms' geographic expansion by fixing firms locations. As the cost of adopting communication technology decreases, more firms opt for adoption, which reduces both d_{os} and h, but firms do not reoptimize their establishment locations. Panel B in Figure 7 shows the corresponding efficiency gains (solid bars) and contrasts with the benchmark results (clear bars). Without geographic expansion, the aggregate efficiency gain decreases from 1.7% to 1.04%, or approximately 40 percent lower.

Moreover, the decrease in efficiency gains varies across locations, which highlights the importance of firms reoptimizing their establishment locations in determining local efficiency gains. Appendix Table F.2 breaks down local efficiency gains by the types of firms: local firms (i.e., firms headquartered in that location) and outside firms (i.e., firms headquartered elsewhere). Outside firms are further categorized into four groups based on their establishment presence before and after the Internet privatization. Stayers (i.e., outside firms that have establishments in the location both before and after the Internet privatization) account for 42% of local efficiency gains in the South Atlantic, whereas new entrants contribute around 28%. In contrast, new entrants contribute 50% to efficiency gains in the Mountain census division. Therefore, the Mountain is disproportionately affected when firms are not allowed to reoptimize their establishment locations. Overall, outside firms account for four-fifths of local efficiency gains, whereas local firms account for the rest.[50]

To further isolate the other two channels, I compute another counterfactual that shuts down the internal communication channel by setting $d_{os}(\overline{\varphi})$ to be the same as $d_{os}(\underline{\varphi})$. In this case, the only benefit from technology adoption is a firm-wide productivity increase.

[50]Appendix F.2 provides more details on the decomposition of efficiency gains.

Figure 7: Decomposing Efficiency Gains from Internet Privatization



Notes: Panel A shows the efficiency gains from the Internet privatization on aggregate (the orange bar on the left) and in each census division (the light blue bars). Panel B fixes firms and their establishment locations (the solid bars) and contrasts to the benchmark results (the clear bars). Panel C further shuts down the improvements in internal communication from technology adoption by equalizing $d_{os}(\varphi)$.

Panel C shows that the aggregate efficiency gains further decrease from 1.04% to 0.77%, or approximately 25 percent lower.

Taken together, the geographic expansion of firms and improvements in internal communication contribute to more than half of the overall efficiency gains. Restricting these two channels would significantly underestimate the benefits from adopting communication technology.

5.2 Policies Reducing ICT Cost

Governments worldwide continue to make significant investments in ICT, such as the U.S. Infrastructure Investment Bill and American Jobs Act, which allocated $65 billion for high-speed Internet access. In this section, I use the model to quantify the efficiency gains from policies that reduce ICT costs and bridge the digital divide.

Panel A of Figure 8 shows the estimated average fixed costs of technology adoption for each census division. The differences in these costs are driven by the location's average distance to NSFNET nodes. In the following, I simulate two policies that reduce the costs of technology adoption—one at the local level and the other at the national level—while keeping both policies with the same total reduction in costs.

5.2.1 Local ICT Cost Reduction

I first simulate a local policy that reduces adoption costs by around 15% in the West South Central census division, including Arkansas, Louisiana, Oklahoma and Texas. For example, local governments might enhance broadband infrastructure, giving firms better access to high-speed Internet and advanced business applications such as intranets. This cost reduction increases the local technology adoption rate by 3.5%. Because of the complementarity between technology adoption and geographic expansion, more local firms become multi-unit. Panel B of Figure 8 shows where these West South Central firms expand their production. New England, which has high productivity, and West North Central, which has low wages, are among the favorite destinations. These expansion patterns suggest that improvements in ICT infrastructure in the South region can affect other regions, particularly those in the North region, through firm expansion.

Panel C shows the distribution of local efficiency gains. As a direct effect, local efficiency in West South Central increases by 0.03%. Moreover, other locations also benefit substantially from this local ICT cost reduction, leading to a 0.013% aggregate efficiency gain. The far-reaching effects are driven by multi-unit production. As shown in Panel D, a trade-only model would predict gains that are geographically confined to the West South Central and decay rapidly in the distance.[51] One key driver of the differences between the two models is the elasticity of communication costs and trade costs with respect to distance. The estimated elasticity of communication costs is 0.072 and 0.181 for intranet adopters and nonadopters, respectively. Even for nonadopters, the elasticity is smaller than that of trade costs with respect to distance. Therefore, firms' multi-unit production is an important channel through which a local shock can spill over across locations.

In Appendix F.2, I break down local efficiency gains into contributions from local and outside firms, further highlighting the role of firm geographic expansion in shaping the distribution of efficiency gains across regions.

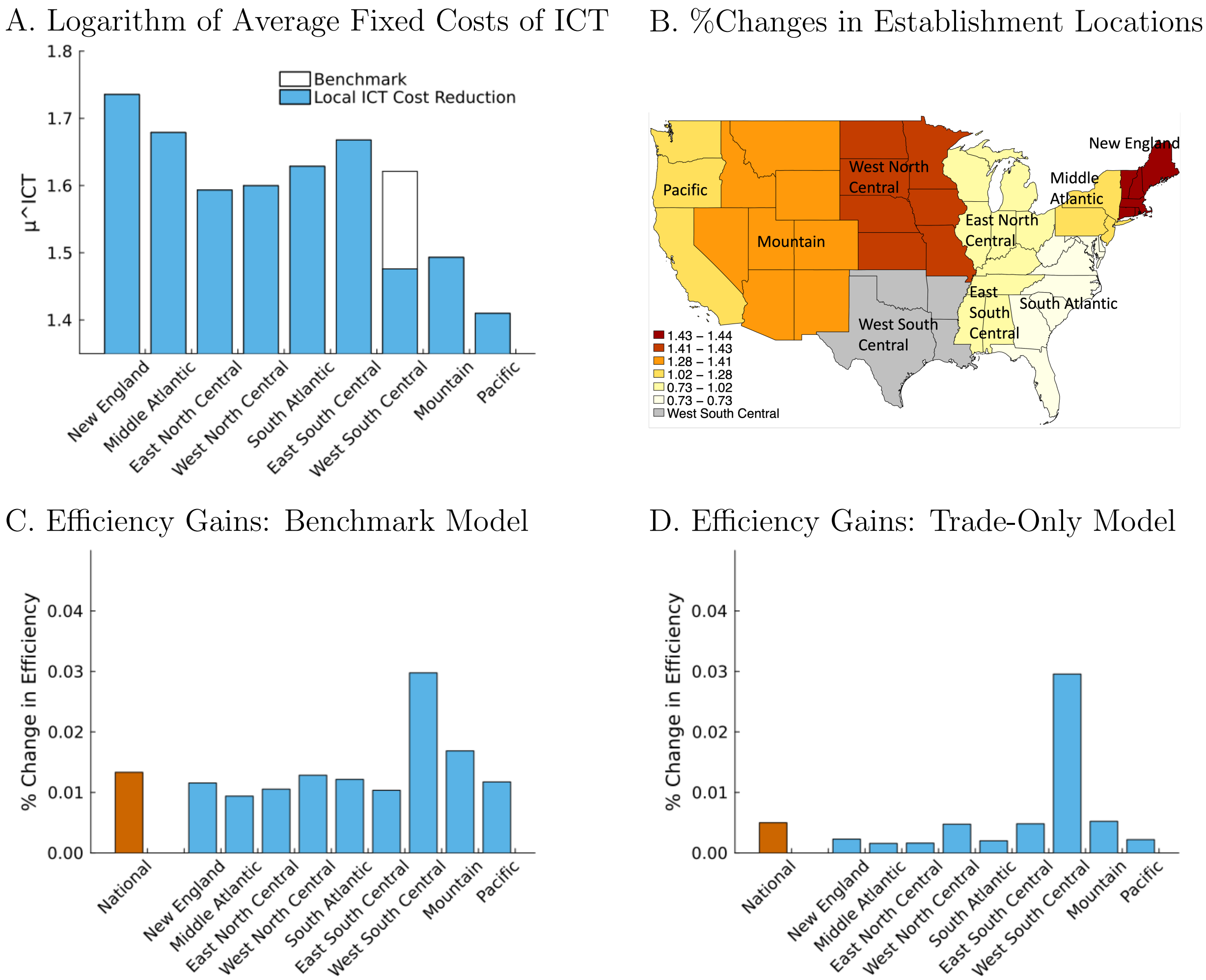
5.2.2 National ICT Cost Reduction

Consider an alternative national policy that lowers the adoption costs for all locations. To capture the notion of reducing the digital divide, which is a central topic of policy debate, I allow the size of the cost reduction to be larger for locations with a higher adoption cost: $|\Delta\mu^{ICT}| \propto \alpha \text{HQ}\widetilde{\text{DistTo}}\text{Node}_o$, where $\text{HQ}\widetilde{\text{DistTo}}\text{Node}_o$ is the average distance to the nearest NSFNET node in the census division o. Parameter α is set such that the aggregate cost reduction in this national policy is the same as that in the previous local policy. In other words, the cost reduction from the local policy is split across locations, disproportionately favoring those with high adoption costs.

Panel A of Figure 9 shows the extent of the cost reduction for different regions, ranging

[51] In a trade-only model, the ICT cost reduction in the West South Central census division is designed to generate the same direct local efficiency gains in the West South Central division as in the benchmark model. The goal is to compare the distributional effects between the benchmark and trade-only models.

Figure 8: Local ICT Cost Reduction

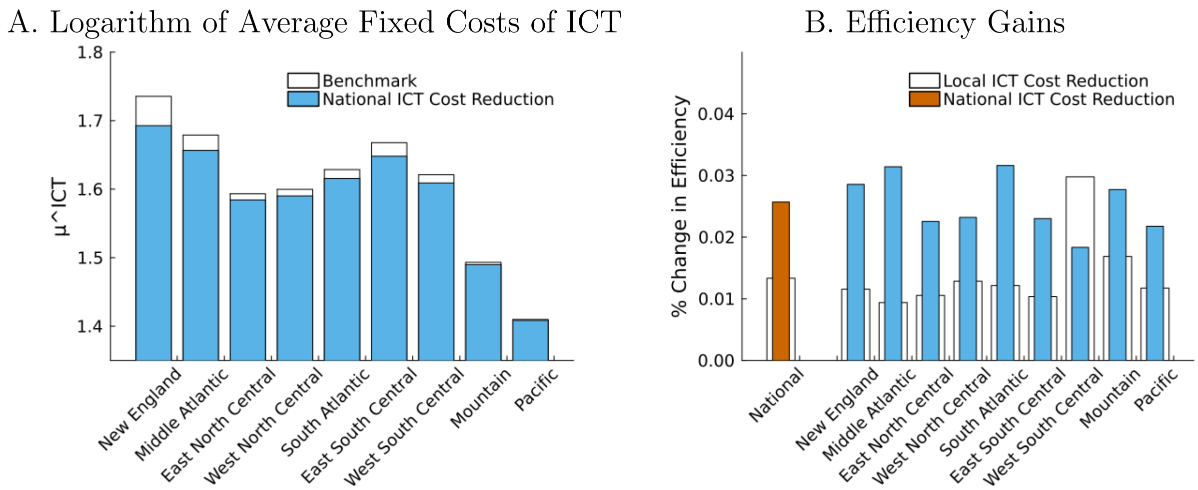


Notes: Panel A displays the log average fixed costs of ICT in each census division and the local policy reducing ICT costs in the West South Central. Panel B presents the changes in the share of West South Central firms that expanded to the other census divisions. Panels C and D show the efficiency gains in the benchmark model and a trade-only model, respectively.

from 4.3% in New England to 0.14% in the Pacific. Panel B compares the resulting efficiency gains (solid bars) with those from the local policy (clear bars). Although the reduction in adoption costs varies across locations, the differences in efficiency gains are smaller, primarily because of the spillover effects of multi-unit production. Even locations that experience smaller reductions in adoption costs, such as the Pacific, can experience significant efficiency gains. With the same cost reduction, the national policy leads to an aggregate efficiency gain of 0.026%, almost doubling that from the local policy.[52]

[52]The BEA reports that manufacturing GDP in 1999 was 1,549.8 billion in 1999 U.S. dollars. Thus, an increase of 0.026% equals approximately 400 million U.S. dollars. An equivalent policy of subsidizing firm ICT adoption would cost approximately 15.5 million U.S. dollars to achieve the same increase in ICT

Figure 9: National ICT Cost Reduction



Notes: Panel A displays the log average fixed costs of ICT in each census division, with locations facing higher costs seeing a greater reduction. Panel B shows the efficiency gains from this national policy (the solid bars) and contrasts to the gains from the local policy reported in Figure 8 Panel C (the clear bars).

Taken together, these results underscore the importance of multi-unit production in evaluating the gains from ICT and policy proposals that lower ICT costs. A coordinated approach to reduce the digital divide across regions can lead to larger overall gains.

6 Conclusion

This paper investigates how ICT affects firms' geographic organization, aggregate efficiency, and policy implications. Using U.S. Census data, I highlight the role of internal communication technology in driving the recent geographic expansion of U.S. firms. Moreover, I quantify a spatial equilibrium model of multi-unit firm location choices and their technology adoption. In the model, firms can improve their internal communication by paying a fixed cost to adopt better technologies that (i) improve firm-wide productivity and (ii) reduce communication costs from headquarters to other establishments, resulting in rich interaction between technology adoption and firms' internal geography. The estimation reveals that adopting internal communication technology—intranet in particular—decreases communication cost elasticity by 50% and enhances firm productivity by 30%.

Policy simulations show that ICT development offers more dispersed efficiency gains when we consider firms' geographic expansion. Therefore, national policies may be more effective than local policies in enhancing ICT access and reducing the digital divide.

adoption.

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Online Appendix: Not for Publication

A Data Appendix

A.1 Computer Network Use Supplement

The Computer Network Use Supplement (CNUS) was a supplemental survey that was part of the 1999 Annual Survey of Manufacturers (ASM). The ASM comprises approximately 50,000 establishments chosen from the universe of manufacturing establishments recorded in the U.S. Census. Of these, approximately 10,000 establishments are chosen with certainty, whereas the remaining 40,000 are selected at random, with larger establishments receiving higher probability.

The CNUS was mailed to all establishments in the 1999 ASM, and the response rate was approximately 82 percent. Although the CNUS respondents represented approximately 11 percent of all U.S. manufacturing establishments in 1999, their employment constituted approximately 50 percent of the total manufacturing employment, 52 percent of all salaries and wages, and over 60 percent of the value of shipments.[53]

The CNUS asked 39 questions related to the establishment's e-commerce activities and e-business process use. In particular, it asked "Which of the following computer networks does this plant use? Mark all that apply. (1) Internet, (2) Intranet, (3) Local area network, (4) EDI network, (5) Extranet, (6) Other, (7) None, and (8) Don't know." The survey also asked whether the plant used online networks, including the Internet, intranet, EDI, or extranet, to share the following types of information: (1) Design specifications, (2) Product catalogs, (3) Demand projections, (4) Order statuses, (5) Production schedules, (5) Inventory data, and (6) Logistics and transportation information.

Table A.1 lists the summary statistics of the CNUS data at the establishment level. The adoption rates of different networks and communication patterns are comparable to those at the firm level, as reported in Table 1.

A.2 Longitudinal Business Database

The Longitudinal Business Database (LBD) covers the universe of U.S. establishments since 1976 and is updated annually. The LBD provides consistent identifiers at the establishment (LBDNUM) and firm (FIRMID) levels, which allows me to link establishments to their parent firms and track the firms over time. The data also record the establishment location's ZIP code, county, and state; employment; annual payroll; and industry codes constructed by Fort and Klimek (2018). Table A.2 reports the summary statistics of the manufacturing

[53]Census reports can be found at `https://www.census.gov/library/publications/2002/econ/1999-e-stats-mcd.html`

firms in the LBD for the census years between 1977 and 2012, i.e., years ending 7 or 2. Approximately 4% of these firms are multi-unit firms with more than one establishment.

The estimation, particularly the reduced-form analysis of the Internet privatization, relies on a balanced panel of firms in the LBD from 1987 to 2007. Table A.3 shows the summary statistics of this sample. It includes approximately 33,500 firms and thus 702,000 firm-year observations for the twenty-one years ranging from 1987 to 2007. I further link firms in the balanced sample with the 1999 CNUS data to perform structural estimation. Approximately 14% of the firms in the LBD balanced sample are matched to the CNUS.

A.3 Identifying Firm Headquarters

Firms can be categorized into three types: (i) single-unit firms, (ii) multi-unit firms with standalone headquarters, and (iii) multi-unit firms with integrated headquarters.

First, I obtain the location and employment of single-unit firms from the Longitudinal Business Database (LBD). If there is only one establishment associated with an FIRMID, then that establishment is considered the headquarters.

Second, to identify the standalone headquarters of multi-unit firms, I augment the LBD with the Census of Auxiliary Establishments (AUX). According to the Census Bureau, auxiliary establishments do not engage in production; rather, they are engaged in management, supervision, general administrative functions, and supporting services for other establishments within the same enterprise, thereby serving as, for example, corporate headquarters, R&D and testing laboratories, warehouses and so forth. The AUX is collected every five years (census years that end in 2 and 7). I follow the procedure in Aarland et al. (2007) and Giroud (2013) to identify these standalone headquarters of multi-unit firms. Prior to 1997, the AUX provided a detailed breakdown of the employment of administrative and managerial employees, office and clerical employees, R&D and testing employees, warehousing employees, sales employees, and so forth. An establishment is identified as a headquarters if its total employment in administrative, managerial, and clerical work is greater than its employment in any of the other types of work. Since 1997, headquarters have been classified with NAICS code 551114. While many firms have only one headquarters identified, some firms have multiple establishments identified as their headquarters.[54] In this case, I use Standard Statistical Establishment Listing (SSEL) to obtain the establishment's name and consider an establishment the headquarters if its name includes the word "headquarters." After these two rounds of selection, if a firm still has multiple headquarters identified, then

[54]In the reduced-form analysis, I use the firm's headquarters locations at the beginning of the sample period in 1987 to construct the firm's distance to the nearest NSFNET node.

I choose the one with the largest payroll as the headquarters. Salaries are often higher for employees engaging in management, e.g., executives.

Third, for multi-unit firms that integrate their headquarters with manufacturing units, I choose the establishment with the largest payroll as the headquarters for these firms.

B Empirical Motivation Appendix

In Appendix B.1, I clarify the relationship between within-industry geographic expansion, the focus of this paper, and overall expansion. In Appendix Section B.2, I explain how to fit the increasing geographic expansion of multi-unit firms with the overall decline of the U.S. manufacturing sector. In Appendix Section B.3, I provide robustness checks of the relationship between ICT adoption and firms' geographic expansion.

B.1 Decomposing Firms' Span of Control

To focus on the firm's geographic expansion, I consider a firm at the FIRMID–industry level. I first clarify how this definition of a firm is related to that using FIRMID.

Denote firm at the FIRMID level by i. Let N_i^{est} and N_i^{ind} denote the number of establishments and the number of industries in which firm i operates, respectively. Denote the industry by j. Let N_{ij}^{est} denote the number of establishments that firm i owns in industry j. Then, we can decompose the firm's overall span of control (i.e., the average number of establishments belonging to the same FIRMID) into two components—one reflecting the firm's industrial span of control (i.e., the average number of industries in which a firm operates) and the other reflecting its within-industry geographic span of control (i.e., the average number of establishments that a firm owns within an industry):

$$\underbrace{\frac{\sum_{i=1}^{N^{\text{firm}}} N_i^{\text{est}}}{N^{\text{firm}}}}_{\substack{\text{avg. number of establishments} \\ \text{per FIRMID}}} = \underbrace{\frac{\sum_{i=1}^{N^{\text{firm}}} \sum_{j=1}^{N_i^{\text{ind}}} N_{ij}^{\text{est}}}{\sum_{i=1}^{\text{firm}} N_i^{\text{ind}}}}_{\substack{\text{avg. number of establishments} \\ \text{per FIRMID–industry}}} \underbrace{\frac{\sum_{i=1}^{\text{firm}} N_i^{\text{ind}}}{N^{\text{firm}}}}_{\substack{\text{avg. number of industries} \\ \text{per FIRMID}}} .$$

The first term on the right-hand side is equivalent to the average number of establishments of firms at the FIRMID–industry level, representing the firm's within-industry expansion across locations.

B.2 Span of Control for US Manufacturers

This section of the appendix examines the trend of increasing within-industry geographic expansion of multi-unit firms and relates it to the overall decline of the U.S. manufacturing sector.

Appendix Figure A.1 displays the span of control for manufacturing multi-unit firms. Panel A shows that the average number of establishments per FIRMID–industry has been increasing over time for those multi-unit firms. Meanwhile, it is well-documented that employment and the number of establishments in the manufacturing sector have been declining since the late 1990s.

To reconcile these two phenomena, we need to consider two additional margins. The first is the firm's industry scope, as explained in the previous appendix section. Panel B shows the average number of industries per FIRMID, which has decreased over time.[55] Combined with the firm's within-industry geographic expansion, Panel C shows that the overall number of manufacturing establishments belonging to the same FIRMID first declined in the 1980s, driven by the decreasing number of industries, and then rose from the late 1990s, driven by the increasing number of establishments within industries, i.e., geographic expansion.[56]

The second margin is the total number of multi-unit firms, as shown in Panel D. The number of multi-unit firms in the manufacturing sector increased before the late 1990s but has been decreasing since then, which is consistent with the overall trend of the total number of manufacturing establishments documented in Fort et al. (2018). This decline in the number of multi-unit firms offsets the increase in the number of establishments per firm, leading to an overall decline in the number of establishments.

Finally, the increasing trend in Panel A is not solely due to selection. The number of establishments of firms that continue to operate in an industry throughout the period has increased, reflecting firm expansion across locations. These multi-unit firms are large firms, accounting for a significant share of employment and output. Additionally, Rossi-Hansberg et al. (2021) document that the rising U.S. industry concentration is driven by top firms opening more establishments across locations. Therefore, understanding the role of ICT in the geographic expansion of multi-unit firms is important for studying the aggregate implications of ICT growth, as well as policies that improve ICT access.

[55] I consider firms and their establishments in the manufacturing sector. Industries are manufacturing industries with two-digit NAICS codes ranging from 31 to 33.

[56] As Panel A shows the average number of establishments per FIRMID–industry for multi-unit firms, excluding single-unit firms, the product of the values in Panel A and Panel B does not necessarily equal that in Panel C.

B.3 ICT Adoption and Firm Geographic Expansion: Robustness

I show that the relationship between a firm's ICT adoption and its geographic expansion is robust to defining a firm by FIRMID. Column (1) of Table B.2 shows the baseline results of Equation (1), where a firm is defined by a FIRMID–industry pair and focuses on firms and their establishments in the manufacturing sector.

Single-industry firms. For the first robustness check, I restrict the sample to firms that operate in only one industry. In this case, the definition of the firm is the same either way, and the firm's scope is solely determined by its geographic scope. The results in Column (2) show that the growth rate in the number of establishments is strongly correlated with intranet adoption, whereas other types of network adoption have weaker or no correlation.

Firm expansion in all sectors. In the second set of robustness checks, I define a firm by FIRMID and consider its expansion in all sectors, including nonmanufacturing sectors. Columns (3)–(5) in Table B.2 use the growth rate in the firm's number of establishments in all sectors, the growth rate in the firm's employment in all sectors, and the growth rate in the share of manufacturing employment, respectively, as dependent variables. The estimated coefficients indicate that firms adopting networks are associated with a higher growth rate in the number of establishments and employees across all sectors, with an intranet being the most strongly correlated with a firm's overall expansion. Column (5) shows that the correlation between the growth rate in the share of manufacturing employment and network adoption is economically small and statistically insignificant. As firms expand into all sectors, they do not exhibit disproportionate expansion into the nonmanufacturing sector.

C Model Appendix

C.1 The Consumer's Problem

Denote the firm by i and its headquarters location by o. As each firm produces a continuum of varieties ω, each product can be denoted by a firm–variety combination (i, ω). The consumer's location is denoted by k, aggregate consumption is denoted by Y_k, and expenditure is denoted by E_k. Denote the price index by P_k such that $E_k = P_k Y_k$. In each location k, given the product prices $p_{ok}(i, \omega)$ and total expenditure E_k, the consumer's problem is

$$\max_{\{y_{ok}(i,\omega)\}_{\omega,i,o}} \left(\sum_{o=1}^{N} \int_0^{m_o} \left(\int_0^1 y_{ok}(i,\omega)^{\frac{\rho-1}{\rho}} d\omega \right)^{\frac{\rho}{\rho-1}\frac{\sigma-1}{\sigma}} di \right)^{\frac{\sigma}{\sigma-1}},$$

subject to the budget constraint $\sum_{o=1}^{N}\int_0^{m_o}\int_0^1 p_{ok}(i,\omega)y_{ok}(i,\omega)d\omega di \leq E_k$.

The first-order condition for product (i,ω) is

$$Y_k^{1/\sigma}\left(\int_0^1 y_{ok}(i,\omega)^{\frac{\rho-1}{\rho}}\right)^{\frac{\rho}{\rho-1}\frac{\sigma-1}{\sigma}-1} y_{ok}(i,\omega)^{-1/\rho} = \mu p_{ok}(i,\omega) \tag{21}$$

where $Y_k \equiv \left(\sum_{o=1}^{N}\int_0^{m_o}\left(\int_0^1 y_{ok}(i,\omega)^{\frac{\rho-1}{\rho}}d\omega\right)^{\frac{\rho}{\rho-1}\frac{\sigma-1}{\sigma}} di\right)^{\frac{\sigma}{\sigma-1}}$.

Similarly, we can derive the first-order conditions for other products (i',ω'). By the budget constraint, the inverse demand for each product (i,ω) from location k is

$$\begin{aligned} p_{ok}(i,\omega) &= y_{ok}(i,\omega)^{-1/\rho}y_{ok}(i)^{1/\rho-1/\sigma}Y_k^{1/\sigma}P_k, \quad \text{or equivalently,} \\ y_{ok}(i,\omega) &= p_{ok}(i,\omega)^{-\rho}y_{ok}(i)^{1-\rho/\sigma}Y_k^{\rho/\sigma}P_k^{\rho}, \end{aligned} \tag{22}$$

where $y_{ok}(i) \equiv \left(\int_0^1 y_{ok}(i,\omega)^{\frac{\rho-1}{\rho}}d\omega\right)^{\frac{\rho}{\rho-1}}$. In the case where $\rho=\sigma$, $y_{ok}(i,\omega) = p_{ok}(i,\omega)^{-\sigma}E_kP_k^{\sigma-1}$.

Integrating $y_{ok}(i,\omega)^{\frac{\rho-1}{\rho}}$ in (22) over firm i's varieties $\omega\in[0,1]$, we have that

$$y_{ok}(i) = \left(\int_0^1 y_{ok}(i,\omega)^{\frac{\rho-1}{\rho}}d\omega\right)^{\frac{\rho}{\rho-1}} = y_{ok}(i)^{1-\rho/\sigma}Y_k^{\rho/\sigma}P_k^{\rho}\left(\int_0^1 p_{ok}(i,\omega)^{1-\rho}d\omega\right)^{\frac{\rho}{\rho-1}}$$

By reorganizing the terms, we can get the firm-level demand function $y_{ok}(i) = Y_kP_k^{\sigma}p_{ok}(i)^{-\sigma}$, where $p_{ok}(i) \equiv \left(\int_0^1 p_{ok}(i,\omega)^{1-\rho}d\omega\right)^{\frac{1}{1-\rho}}$. Plugging this into (22), we can rewrite the demand function for product (i,ω) from location k as

$$y_{ok}(i,\omega) = p_{ok}(i,\omega)^{-\rho}p_{ok}(i)^{\rho-\sigma}P_k^{\sigma}Y_k. \tag{23}$$

Integrating $y_{ok}(i)^{\frac{\sigma}{\sigma-1}}$ over all firms, we have that

$$Y_k = \left(\sum_{o=1}^{m_o}\int_0^{m_o} y_{ok}(i)^{\frac{\sigma-1}{\sigma}}di\right)^{\frac{\sigma}{\sigma-1}} = Y_kP_k^{\sigma}\left(\sum_{o=1}^{m_o}\int_0^{m_o} p_{ok}(i)^{1-\sigma}di\right)^{\frac{\sigma}{\sigma-1}}, \tag{24}$$

which gives us the following expression for the price index for each location k:

$$P_k = \left(\sum_{o=1}^{m_o}\int_0^{m_o} p_{ok}(i)^{1-\sigma}di\right)^{\frac{1}{1-\sigma}} = \left[\sum_{o=1}^{m_o}\int_0^{m_o}\left(\int_0^1 p_{ok}(i,\omega)^{1-\rho}d\omega\right)^{\frac{1-\sigma}{1-\rho}}di\right]^{\frac{1}{1-\sigma}}. \tag{25}$$

C.2 The Firm's Problem Given Its Set of Locations and ICT

This section of the appendix provides more details on the derivation of the firm's sales, given a set of establishment locations and the state of its ICT, and the derivation of the within-firm sales distribution across establishments.

Let o denote the firm's headquarters location, z denote the firm-specific productivity, S denote the set of establishment locations in which the firm operates, and φ denote the ICT level. As the production function has constant returns to scale and uses labor as the only input, the unit cost of producing a variety ω at its establishment at location s and shipping to market k is $c_{oks}(\omega,\varphi,z) = (z\varepsilon_s(\omega))^{-1}w_s\tau_{sk}\gamma_{os}(\varphi)$, where $\varepsilon_s(\omega)$ is establishment-specific productivity, which follows a Fréchet distribution and is independently and identically distributed across locations and varieties; w_s is the wage rate at location s; τ_{sk} is the shipping cost between location s and market k; and $\gamma_{os}(\varphi)$ is the communication cost between headquarters location o and establishment location s.

In each market, there exists a representative consumer who makes consumption decisions independently. Owing to the constant-returns-to-scale production function at the establishment level, the firm chooses the establishment with the lowest unit cost to serve each market. That is, for any variety $\omega \in [0,1]$, the actual cost to market k is $c_{ok}(\omega,S,\varphi,z) = \min_{s\in S} c_{oks}(\omega,\varphi,z)$. Let variety $\omega \in [0,1]$ be given. Since establishment productivity $\varepsilon_s(\omega)$ follows a Fréchet distribution with scale parameter T_s and shape parameter θ and is i.i.d. across locations, we can derive the distribution of the lowest unit cost for market k as follows:

$$
\begin{aligned}
P(c_{ok}(\omega,S,\varphi,z) \le c) &= 1 - P(c_{ok}(\omega,S,\varphi,z) > c) = 1 - P(\min_{s\in S} c_{oks}(\omega,\varphi,z) > c) \\
&= 1 - \prod_{s\in S} P(c_{oks}(\omega,\varphi,z) > c) = 1 - \prod_{s\in S} P((z\varepsilon_s(\omega))^{-1}w_s\tau_{sk}\gamma_{os}(\varphi) > c) \\
&= 1 - \prod_{s\in S} P(\varepsilon_s(\omega) < (cz)^{-1}w_s\tau_{sk}\gamma_{os}(\varphi)) = 1 - \prod_{s\in S} e^{-\left((cz)^{-1}T_s^{-1}w_s\tau_{sk}\gamma_{os}(\varphi)\right)^{-\theta}} \\
&= 1 - e^{-c^\theta z^\theta \sum_{s\in S} T_s^\theta (w_s\tau_{sk}\gamma_{os}(\varphi))^{-\theta}} \equiv 1 - e^{-c^\theta z^\theta \tilde{\Phi}_{ok}(S,\varphi)},
\end{aligned}
$$

where $\tilde{\Phi}_{ok}(S,\varphi) \equiv \sum_{s\in S} T_s^\theta \left(w_s\tau_{sk}\gamma_{os}(\varphi)\right)^{-\theta}$ summarizes the production potential of the firm to market k, including the states of technology, input costs, market access, and costs of communication with the headquarters of all the establishment locations.

As demand has constant elasticity of substitution, the firm charges a constant markup over the marginal cost, which is the same as the unit cost in this case, with a factor of $\sigma/(\sigma-1)$. Thus, the distribution of the price of variety ω that the firm charges in market k

(i.e., $p_{ok}(\omega, S, \varphi, z)$) has the following cumulative distribution function:

$$P(p_{ok}(\omega, S, \varphi, z) \leq p) = 1 - e^{-\left(\frac{\sigma-1}{\sigma}\right)^{\theta} p^{\theta} z^{\theta} \tilde{\Phi}_{ok}(S,\varphi)}. \tag{26}$$

Then, we can derive the firm-level price index

$$p_{ok}(i)^{1-\rho} = \int_0^1 p_{ok}(i, \omega)^{1-\rho} d\omega = \int_0^{\infty} \tilde{p} dF(\tilde{p}), \tag{27}$$

where $\tilde{p} = p^{1-\rho}$, $F(\tilde{p}) = P(\tilde{p}_{ok}(i, \omega) \leq \tilde{p}) = 1 - e^{-\left(\frac{\sigma-1}{\sigma}\right)^{\theta} \tilde{p}^{\frac{\theta}{1-\rho}} z^{\theta} \tilde{\Phi}_{ok}(S,\varphi)} = 1 - e^{-a\tilde{p}^{\frac{\theta}{1-\rho}}}$, and $a = \left(\frac{\sigma-1}{\sigma}\right)^{\theta} z^{\theta} \tilde{\Phi}_{ok}(S, \varphi)$. Denote $t = a\tilde{p}^{\frac{\theta}{1-\rho}}$ so that $\tilde{p} = (t/a)^{\frac{1-\rho}{\theta}}$. Then, we can derive the firm price index as

$$\begin{aligned} p_{ok}(i) &= (\int_0^{\infty} \tilde{p} dF(\tilde{p}))^{1/(1-\rho)} = (\int_0^{\infty} (t/a)^{\frac{1-\rho}{\theta}} d(1 - e^{-t}))^{1/(1-\rho)} \\ &= \Gamma\left(\frac{\theta + 1 - \rho}{\theta}\right)^{1/(1-\rho)} \left(\frac{\sigma}{\sigma - 1}\right) z^{-1} \tilde{\Phi}_{ok}(S, \varphi)^{\frac{-1}{\theta}} \end{aligned} \tag{28}$$

By the demand function in Equation (23), the sales of variety ω of the firm to market k are

$$\text{sales}_{ok}(\omega, i) = p_{ok}(\omega, i) y_{ok}(\omega, i) = E_k P_k^{\sigma-1} p_{ok}(i, \omega)^{1-\rho} p_{ok}(i)^{\rho-\sigma}, \forall \omega \in [0, 1] \tag{29}$$

Therefore, the total sales of the firm to market k are

$$\begin{aligned} \text{sales}_{ok}(S, \varphi, z) &= E_k P_k^{\sigma-1} p_{ok}(i)^{\rho-\sigma} \int_0^1 p_{ok}(i, \omega)^{1-\rho} d\omega = E_k P_k^{\sigma-1} p_{ok}(i)^{1-\sigma} d\omega \\ &= \Gamma\left(\frac{\theta - \rho + 1}{\theta}\right)^{\frac{1-\sigma}{1-\rho}} \left(\frac{\sigma - 1}{\sigma}\right)^{\sigma-1} \left(\frac{z}{h(\varphi)}\right)^{\sigma-1} E_k P_k^{\sigma-1} \Phi_{ok}(S, \varphi)^{\frac{\sigma-1}{\theta}}, \end{aligned} \tag{30}$$

where $\Phi_{ok}(S, \varphi) \equiv \sum_{s \in S} T_s^{\theta} (w_s \tau_{sk} d_{os}(\varphi))^{-\theta}$. I assume that $\theta - \rho + 1 > 0$ so that $\Gamma(\cdot)$ is properly defined.

The firm's profit $\pi_{ok}(S, \varphi, z)$ is given by

$$\begin{aligned} \pi_{ok}(S, \varphi, z) &= \frac{1}{\sigma} \text{sales}_{ok}(S, \varphi, z) \\ &= \frac{(\sigma - 1)^{\sigma-1}}{\sigma^{\sigma}} \Gamma\left(\frac{\theta - \rho + 1}{\theta}\right)^{\frac{1-\sigma}{1-\rho}} \left(\frac{z}{h(\varphi)}\right)^{\sigma-1} E_k P_k^{\sigma-1} \Phi_{ok}(S, \varphi)^{\frac{\sigma-1}{\theta}} \end{aligned} \tag{31}$$

C.3 Within-Firm Sales Distribution

Due to the properties of the Fréchet distribution of establishment-specific productivity, the share of sales to market k that is generated from the establishment in location $s \in S$ equals the share of varieties that have the lowest unit costs in location s. That is,

$$\zeta_{ok\leftarrow s}(S,\varphi) \equiv \frac{\text{sales}_{ok\leftarrow s}(S,\varphi,z)}{\text{sales}_{ok}(S,\varphi,z)} = \frac{(T_s/w_s)^{\theta} d_{os}(\varphi)^{-\theta}\tau_{sk}^{-\theta}}{\Phi_{ok}(S,\varphi)}. \tag{32}$$

Following Equation (32), the share of the firm's total sales generated by a nonheadquarters establishment at s is:

$$\begin{aligned}
\zeta_{os}(S,\varphi) &= \frac{\sum_k \text{sales}_{ok\leftarrow s}(S,\varphi)}{\sum_k \text{sales}_{ok}(S,\varphi)} = \frac{\sum_k \text{sales}_{ok}(S,\varphi)\times \zeta_{ok\leftarrow s}(S,\varphi)}{\sum_k \text{sales}_{ok}(S,\varphi)} \\
&= \left(\frac{T_s}{w_s}\right)^{\theta} d_{os}(\varphi)^{-\theta} \sum_k \left(\frac{E_k P_k^{\sigma-1}\Phi_{ok}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}}{\sum_{k'} E_{k'} P_{k'}^{\sigma-1}\Phi_{ok'}(S,\varphi)^{\frac{\sigma-1}{\theta}}}\tau_{sk}^{-\theta}\right).
\end{aligned} \tag{33}$$

Similarly, the sales share accounted for by the firm's headquarters at o is:

$$\zeta_{oo}(S,\varphi) = \left(\frac{T_o}{w_o}\right)^{\theta} d_{oo}(\varphi)^{-\theta} \sum_k \left(\frac{E_k P_k^{\sigma-1}\Phi_{ok}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}}{\sum_{k'} E_{k'} P_{k'}^{\sigma-1}\Phi_{ok'}(S,\varphi)^{\frac{\sigma-1}{\theta}}}\tau_{ok}^{-\theta}\right). \tag{34}$$

Combining Equations (33) and (34), we can derive the logarithm of the sales share at nonestablishment locations $s \in S, s \neq o$, normalized by the logarithm of the headquarters sales share, as:

$$\begin{aligned}
\log \tilde{\zeta}_{os}(S,\varphi) &\equiv \log \zeta_{os}(S,\varphi) - \log \zeta_{oo}(S,\varphi) \\
&= -\theta \log d_{os}(\varphi) + \log\left(\frac{\sum \omega_{ok}(S,\varphi)\tau_{sk}^{-\theta}}{\sum \omega_{ok}(S,\varphi)\tau_{ok}^{-\theta}}\right) + \theta\log(T_s/T_o) - \theta \log(w_s/w_o),
\end{aligned} \tag{35}$$

where $\omega_{ok}(S,\varphi) \equiv \frac{E_k P_k^{\sigma-1}\Phi_{ok}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}}{\sum_{k'} E_{k'} P_{k'}^{\sigma-1}\Phi_{ok'}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}}$. To obtain the second equality, I use the assumption that $d_{oo}(\varphi) = 1$ and add and subtract the term $\sum_{k'} E_{k'} P_{k'}^{\sigma-1}\Phi_{ok'}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}$.

C.4 Equilibrium

I consider two equilibriums with different assumptions on labor markets, namely, the baseline features perfectly elastic labor supply and an extension with perfectly inelastic labor supply. The reality likely falls somewhere in between these two scenarios.

Elastic labor supply (Baseline). I assume that the nonmanufacturing sector is large enough to pin down the wage; thus, wages are treated as exogenous. The equilibrium is a vector of prices $\boldsymbol{P}$ consistent with firm optimization in (7) to (10) and clears the product market for each location $k = 1, \cdots, N$:

$$\eta G_k = P_k Y_k, \tag{36}$$

where $P_k = \left(\sum_{o=1}^{N} \int_Z p_{ok}(z)^{1-\sigma} d\mu_o(z) \right)^{\frac{1}{1-\sigma}}$ and $Y_k = \left(\sum_{o=1}^{N} \int_Z y_{ok}(z)^{\frac{\sigma-1}{\sigma}} d\mu_o(z) \right)^{\frac{\sigma}{\sigma-1}}$. Here, μ_o denotes the exogenous measure of firms headquartered in location o, and Z denotes the support of firm productivity. $p_{ok}(z)$ and $y_{ok}(z)$ are the firm-level price index and sales, respectively, to market k from a firm headquartered in location o and with productivity z.[57]

The equilibrium price indices affect total output not only through demand but also, importantly, through firms' ICT choices and production location choices.

Inelastic labor supply. Now, I incorporate endogenous wages by assuming that the representative consumer in each location inelastically supplies L_s units of labor. The labor market clearing condition is

$$L_s = \int_Z l_{ss}(z) d\mu_s(z) + \sum_{o \neq s} \int_Z \mathbb{1}[s \in S_o(z)] l_{os}(z) d\mu_o(z), \forall s = 1, \cdots, N. \tag{37}$$

The first term in the right-hand side is the labor demand from local firms, and the second term is the labor demand from the local establishments set up by firms headquartered in other locations.

Moreover, the consumer spends a constant fraction (η) of total income on manufacturing products. The product market clearing condition is

$$P_s Y_s = \eta (w_s L_s + \int_Z \pi_s(z) d\mu_s(z) + F_s + I_o^{\text{other}}) \tag{38}$$

$$\text{where } F_s = \sum_{o \neq s} \int_Z \mathbb{1}[s \in S_o(z)] f_{os}^X(z) d\mu_o(z) + \int_Z f_s^{ICT}(z) d\mu_o(z) \tag{39}$$

is the total fixed costs. These fixed costs and profits from local firms are remitted to the local consumer. I_o^{nonmfg} is the total income from the nonmanufacturing sector.

The equilibrium is characterized by a vector of prices $\boldsymbol{P}$ and wages $\boldsymbol{w}$ consistent with consumer and firm optimization, and clear the labor market and product market for each location.

[57]Specifically, $p_{ok}(z) = (\int_0^1 p_{ok}^{1-\sigma}(z, \omega) dw)^{1/(1-\sigma)} = \tilde{\Gamma} \frac{\sigma}{\sigma-1} \frac{1}{z} \Phi_{ok}(S, \varphi)^{-1/\theta}$ and $y_{ok}(z) = E_k P_k^{\sigma-1} p_{ok}(z)^{1-\sigma}$.

C.5 ICT Cost Reduction and Firm Location Choices

This section of the appendix uses the same three-location example to illustrate the effects of an ICT cost reduction on firm location choices. Those firms on the margin between one and two or two and three establishments are mostly affected by the equilibrium force at the extensive margin.

In equilibrium, an ICT cost reduction affects the firm's geographic span of control through two channels. As a direct effect, firms are more likely to adopt ICT, which leads to expansion due to complementarity between the two decisions. As an indirect effect, markets become more competitive because of increasing firm efficiency, which leads to contraction. The relative strength of the direct and indirect effects determines the net changes in the firm's geographic span of control in equilibrium.

Figure B.1 decomposes the equilibrium effects into direct and indirect effects in the three-location example. Panel A shows the direct effect, in which equilibrium prices are held constant. The solid line represents the policy function of ICT adoption and location choice when the ICT cost is high, which is the same as that in Panel B of Figure 4. The black fragment corresponds to the productivity range in which firms maintain a low ICT level, and the red fragment corresponds to firms that adopt better ICT. The dotted line represents the policy function with a lower ICT cost and with the prices held constant. As the ICT cost declines, all firms with midrange productivity, particularly those on the left end, can adopt better ICT. The cutoff between one and two establishments is shifted to the left, indicating an increase in the fraction of firms expanding from their headquarters to another location. The direct effect leads to expansion in the firm's geographic span of control.

Panel B adds a dashed line that represents the policy function with a low ICT cost but allows equilibrium prices to adjust endogenously. The cutoff between two and three locations is shifted to the left; those firms on the margin, which always adopt better ICT, have to shrink their geographic coverage owing to tougher competition. The cutoff between one and two locations is also shifted to the right in comparison to the case with fixed prices (i.e., the dotted line). Compared with the likelihood in the high ICT cost case (i.e., the solid line), however, the likelihood of expanding from headquarters to another location increases, driven by the direct effect.

D Reduced-Form Appendix

D.1 National Science Foundation Network

This section of the appendix provides a brief history of the NSFNET from its initiation in 1986 to its ultimate privatization in 1995.

1986-1991: Expansion and Upgrade

The National Science Foundation Network was initiated in 1986, linking the National Center for Atmospheric Research in Boulder, Colorado, and five NSF-sponsored supercomputing centers: the John von Neumann Center in Princeton, New Jersey; the San Diego Supercomputer Center in San Diego, California; the National Center for Supercomputing Applications in Urbana, Illinois; the Cornell Theory Center in Ithaca, New York; and the Pittsburgh Supercomputing Center in Pittsburgh, Pennsylvania. The Internet speed was at 56 Kbit per second, providing a fast connection across the six NSFNET node sites.

During its first two years of operation, the NSFNET experienced its first round of upgrades and expansion. The network was expanded to thirteen nodes, with the seven new nodes located in Salt Lake City, Utah; Palo Alto, California; Seattle, Washington; Lincoln, Nebraska; Houston, Texas; Ann Arbor, Michigan; and College Park, Maryland. Its speed increased to 1.5 Mbit per second (making it a so-called T1 network).[58] Moreover, the NSFNET provided connections to the backbone nodes from regional networks; these regional networks were in turn connected to smaller regional and campus networks.

Starting in 1990, the NSFNET saw its second round of upgrades and expansion. By the end of 1991, the network had added three more nodes, i.e., one in Atlanta, Georgia; another at Argonne National Laboratory in Lemont, Illinois; and another in Cambridge, Massachusetts. Its speed increased to 45 Mbit per second (making it a so-called T3 network). The core backbone equipment was moved to the MCI junction places to ensure robust infrastructure and stable power.

1991–1995: Commercialization and Privatization

The goal of the NSFNET was to facilitate communication, collaboration and information sharing among higher education and research institutes. Commercial usage was restricted by the *Acceptable Use Policy*. With exploding interest and demand from the commercial side, however, these restrictions were gradually lifted.

[58] The NSF partnered with the Merit Network, a consortium of Michigan universities, and industry players including IBM and MCI. In the upgrade and expansion process, IBM provided hardware and software support, and MCI provided fiber-optic circuits at a reduced rate.

In March 1991, the *Acceptable Use Policy* was revised to allow the NSFNET to carry commercial Internet traffic. The Scientific and Advanced Technology Act of 1992 formally authorized the NSF "to foster and support access by the research and education communities to computer networks which may be used substantially for additional purposes if this will tend to increase the networks' overall capabilities."[59] In the spring of 1993, the NSF released a solicitation to the private sector and transitioned to a new Internet architecture; the awards were announced in 1994.[60]

While attempts to commercialize the Internet started in the early 1990s, the "Internet gold rush" did not arrive until the last moment, when the NSFNET backbone was decommissioned in April 1995. The final restrictions on commercial Internet use were lifted. Together with business successes at the time, privatization catalyzed the explosive development of the Internet and related industries. Figure C.1, which is adapted from Table 5.1 in Greenstein (2015), shows the number of Internet service providers listed in *Boardwatch Magazine* during the 1993—1998 period.[61] The number slightly increased from 24 in November 1993 to 35 in January 1995 but jumped to over 2,000 by May 1996, reflecting the rapid development of commercial Internet access that followed the Internet privatization.

Advanced Research Projects Agency Network

The NSFNET was closely related to its predecessor, the ARPANET, which was funded by the Department of Defense since the 1960s. Following the ARPANET, the NSFNET used packet-switching technology and the TCP/IP protocol.[62] The node locations of the NSFNET were also influenced by the ARPANET, whose nodes were mostly located within military bases, federal agencies and university computer science departments. Therefore, the locations of NSFNET nodes were less likely to have been subject to contemporaneous local shocks at the time of the Internet privatization.

D.2 Robustness and Additional Results

This section of the appendix provides additional robustness checks and results for reduced-form evidence from the Internet privatization.

[59]Scientific and Advanced-Technology Act of 1992, S.1146.

[60]Frazer (1996) documents the details of the new network architecture and award winners.

[61]*Boardwatch Magazine* was initially a journal for bulletin board systems. Since the late 1990s, it has become a magazine for the Internet service providers.

[62]In a packet-switching network, data delivered from a source device are broken into packets and reassembled at the target device. The transmission control protocol (TCP) and internet protocol (IP) ensure that these packets reach the target device and are reassembled in the right order.

D.2.1 General Propensity Score

I construct the generalized propensity score of treatment, using firm and location characteristics before the Internet privatization, and apply the inverse propensity score method to reweight (IPW) observations for the difference-in-differences regression.

Denote the firm by i and its covariates by X_i; the generalized propensity score is defined as the conditional distribution of the treatment, i.e., $f_{D|X}$, where the treatment is the distance to the nearest NSFNET node. I assume that conditional on the covariates, the treatment is log-normally distributed with the mean as a function of the covariates; that is,

$$\text{HQDistToNode}_i \mid X_i \sim \log N(X_i\beta, \sigma^2). \tag{40}$$

The covariates X_i are composed of two components. One is a vector of firm-specific characteristics, including the firm's number of establishments and the logarithm of employment. The other is a vector of county-specific characteristics, including the logarithm of the local population, logarithm of median household income, share of the population below the poverty line, share of people over sixty-five years old, share of the Black population, and share of the population with a bachelor's degree and above. I also include the one-year growth rate in these covariates and a full set of state dummies. The conditional distribution of treatment is as follows:

$$\begin{aligned} &f_{\mathrm{D}|X}(\text{HQDistToNode}_i \mid X_i) \\ &\quad = \frac{1}{\text{HQDistToNode}_i\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(\log \text{HQDistToNode}_i - X_i\beta)^2}{2\sigma^2}\right). \end{aligned} \tag{41}$$

Then, we can define the weight as $w_i = f_{\mathrm{D}}/f_{\mathrm{D}|X}$, where the numerator is a required stabilizing factor equal to the marginal distribution of treatment and where the denominator is the generalized propensity score defined above (see Robins et al., 2000). I follow the common approach and assume the marginal distribution to be log-normal; that is, $\text{HQDistToNode}_i \sim \log N(\overline{\mu}, \overline{\sigma})$. Therefore, the weight is given by

$$w_i = \frac{\sigma}{\overline{\sigma}} \exp\left(\frac{(\log \text{HQDistToNode}_i - X_i\beta)^2}{2\sigma^2} - \frac{(\log \text{HQDistToNode}_i - \overline{\mu}))^2}{2\overline{\sigma}^2}\right). \tag{42}$$

I use observations at the beginning of the sample period in 1987 to estimate the parameters (β, σ, $\overline{\mu}$, $\overline{\sigma}$) via the maximum likelihood estimator. To show that the distance measure is not correlated with firm or location characteristics before privatization, I regress the distance on those covariates using the 1987 observations and adjust the regression by the weights specified in Equation (42):

$$\text{HQDistToNode}_i = \alpha + X_i\beta + \alpha_i^{\text{Industry}} + \alpha_i^{\text{State}} + u_i. \tag{43}$$

As industries might cluster in certain regions, I include the industry fixed effect at the 4-digit NAICS level. To account for heterogeneity across states, I include the state fixed effect. Standard errors are clustered at the county level. Figure C.2 plots the coefficients. These estimated coefficients are economically small and statistically insignificant, indicating that, after reweighting, the distance measure is not systematically correlated with firm and location characteristics before the Internet privatization.

D.2.2 Excluding University Towns

Given that many NSFNET nodes were located in university towns, one may be concerned that firms close to those locations might be different from other firms. To address this concern, I restrict the sample to those cities that are not pure university towns. Specifically, I exclude firms headquartered within 250 miles from the nodes at Princeton, Champaign, Ithaca, Palo Alto, Ann Arbor, College Park, and Cambridge. The number of observations in the estimation sample decreases from 702,000 to 429,000. Column (3) of Table D.1 shows that the coefficient is estimated at 0.4 and is statistically significant at the 1% level. This result confirms that proximity to universities is not driving my baseline result.

D.2.3 Intensive-Margin Effects

To highlight firms' expansion at the extensive margin, i.e., their geographic expansion, I compare it to their overall expansion and expansion at the intensive margin, such as in employment. Table D.2 reports the difference-in-differences estimates of the effects of the Internet privatization on firms' employment, employment per establishment, and the wage rate. In line with the estimates for geographic expansion, the estimate for total firm employment is negative and statistically significant at the 10% level, indicating that privatization increased firms' overall size. However, privatization is not found to have a significant effect on establishment size or wages.

D.2.4 Location of New Establishments

I test whether firms close to nodes are more likely to set up establishments close to the nodes. I run the baseline difference-in-differences regression using the average distance from firms' *new establishments* to the nearest NSFNET nodes as the dependent variable. As shown in

Column (1) of Table D.3, the estimated coefficient is positive and statistically significant, indicating that firms headquartered in locations *closer* to nodes—those with better access to ICT—also build new establishments *closer* to the nodes. This is consistent with our premise that interlocutors at both ends of the communication channel need access to ICT. The distance to nodes, however, might be correlated with other location characteristics. Columns (2)–(7) of Table D.3 show the results with the average county characteristics of new establishments as the dependent variables. For instance, Column (2) shows that firms headquartered closer to nodes tend to set up establishments in counties with larger populations; however, the difference is not statistically distinguishable from zero. Overall, these results suggest that firms with better access to the Internet tend to locate new establishments in counties with higher household income and younger populations and with smaller distances to nodes.

D.2.5 Industry Heterogeneity by Shipping Costs

On model implication is that industries facing higher shipping costs are more incentivized to expand their footprints closer to consumers. To test this implication, I categorize industries based on their average shipping distance using the 2012 Commodity Flow Survey. The idea is that a shorter shipping distance implies higher shipping costs. Consistent with the model, Table D.4 shows that the effect of the Internet privatization is driven by industries with high shipping costs. In contrast, the estimated effect is economically small and statistically insignificant for industries with low shipping costs.

E Estimation Appendix

E.1 First-Step: Within-Firm Employment Distribution

This section of the appendix shows that the within-firm employment distribution across establishments is in the same form as the sales distribution described in Equation (12).

Since the production function is a constant return to scale with labor as the only input and firms compete monopolistically, the establishment's wages are proportional to its sales by a factor of $(\sigma-1)/\sigma$. Therefore, we can write the wage bills at establishment $s \in S$ as

$$w_s L_{os}(S,\varphi) = \frac{(\sigma-1)^\sigma}{\sigma^\sigma}\tilde{\Gamma}\left(\frac{z}{h(\varphi)}\right)^{\sigma-1}\left(\frac{T_s}{w_s}\right)^\theta d_{os}(\varphi)^{-\theta}\sum_k E_k P_k^{\sigma-1}\Phi_{ok}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}\tau_{sk}^{-\theta}, \quad (44)$$

and the employment as

$$L_{os}(S,\varphi) = \frac{(\sigma-1)^{\sigma}}{\sigma^{\sigma}}\tilde{\Gamma}\left(\frac{z}{h(\varphi)}\right)^{\sigma-1} T_s^{\theta} w_s^{-(\theta+1)} d_{os}(\varphi)^{-\theta} \sum_k E_k P_k^{\sigma-1} \Phi_{ok}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}} \tau_{sk}^{-\theta}. \quad (45)$$

Similarly, the employment at the headquarters o is

$$L_{oo}(S,\varphi) = \frac{(\sigma-1)^{\sigma}}{\sigma^{\sigma}}\tilde{\Gamma}\left(\frac{z}{h(\varphi)}\right)^{\sigma-1} T_o^{\theta} w_o^{-(\theta+1)} \sum_k E_k P_k^{\sigma-1} \Phi_{ok}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}} \tau_{ok}^{-\theta}, \quad (46)$$

where we take into account that $d_{oo}(\varphi) = 1$.

Then, the log employment share at nonestablishment locations $s \in S, s \neq o$, normalized by the logarithm of the headquarters employment share, can be written as

$$\begin{aligned} \log \tilde{\zeta}_{os}(S,\varphi) &\equiv \log \zeta_{os}(S,\varphi) - \log \zeta_{oo}(S,\varphi) = \log L_{os}(S,\varphi) - \log L_{oo}(S,\varphi) \\ &= -\theta \log d_{os}(\varphi) + \log\left(\frac{\sum_k \omega_{ok}(S,\varphi)\tau_{sk}^{-\theta}}{\sum_k \omega_{ok}(S,\varphi)\tau_{ok}^{-\theta}}\right) + \theta \log\left(\frac{T_s}{T_o}\right) - (\theta+1)\log\left(\frac{w_s}{w_o}\right), \end{aligned} \quad (47)$$

where $\omega_{ok}(S,\varphi) \equiv \frac{E_k P_k^{\sigma-1} \Phi_{ok}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}}{\sum_{k'} E_{k'} P_{k'}^{\sigma-1} \Phi_{ok'}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}}$. Note that this equation is of the same form as the within-firm sales distribution in Equation (12), except for the coefficient on the relative wages term $\log(w_s/w_o)$.

Parameterization. I approximate the market access by $\log(\sum_k \omega_{ok}(S,\varphi)\tau_{sk}^{-\theta}) \approx (\phi + \phi_o(S,\varphi)) \log \overline{MA}_s$, where $\log \overline{MA}_s \equiv \log(\sum_k \tilde{\omega}_k \tau_{sk}^{-\theta})$ and $\tilde{\omega}_k$ is the local income share. Then, Equation (47) can be written as

$$\begin{aligned} \log \tilde{\zeta}_{os}(S,\varphi) &= -\theta \log d_{os}(\varphi) + \phi_o(S,\varphi) \log \overline{MA}_s \underbrace{+\phi \log \overline{MA}_s + \theta \log T_s - (\theta+1)\log w_s}_{\xi_s} \\ &\quad \underbrace{- \log(\sum_k \omega_{ok}(S,\varphi)\tau_{ok}^{-\theta}) - \theta \log T_o - (\theta+1)\log w_o}_{\xi_o(S,\varphi)} \\ &= -\theta \log d_{os}(\varphi) + \phi_o(S,\varphi)\log \overline{MA}_s + \xi_s + \xi_o(S,\varphi), \end{aligned} \quad (48)$$

Using the firm's intranet adoption as a proxy for φ, we have $\log d_{os}(\varphi) = (\beta_1^d + \beta_2^d \times \text{Intranet}_i) \log \text{Miles}_{os}$, $\phi_o(S,\varphi) = \phi_{oS1} + \phi_{oS2} \times \text{Intranet}_i$, and $\xi_o(S,\varphi) = \xi_{oS1} + \xi_{oS2} \times \text{Intranet}_i$. Plugging these expressions into the equation above, we have the following estimation equation:

$$\log \tilde{\zeta}_{ioS,s} = -\theta\beta_1^d \log \text{Miles}_{os} - \theta\beta_2^d \log \text{Miles}_{os} \times \text{Intranet}_i$$
$$+\phi_{oS1} \log \overline{MA}_s + \phi_{oS2} \log \overline{MA}_s \times \text{Intranet}_i$$
$$+\xi_{oS1} + \xi_{oS2} \times \text{Intranet}_i + \xi_s + \varepsilon_{ioS,s}, \tag{49}$$

where $\varepsilon_{ioS,s}$ is the error term that is orthogonal to the firm's location choice when we take the equation to data.

E.2 Third-Step: Solving Firm Location Choice Problem

This section of the appendix demonstrates that the single crossing differences condition in Arkolakis et al. (2023) applies to my particular settings and provides a brief explanation of the computation algorithm.

Single crossing differences condition. Let the firm's headquarters location o, productivity z, and ICT level φ be given. The firm's total profit from all markets, net of the fixed costs of setting up establishments, are

$$\pi_o(S,\varphi,z) = \frac{\sigma^{-\sigma}}{(\sigma-1)^{1-\sigma}} \tilde{\Gamma} \left(\frac{z}{h(\varphi)}\right)^{\sigma-1} \sum_k E_k P_k^{\sigma-1} \Phi_{ok}(S,\varphi)^{\frac{\sigma-1}{\theta}} - \sum_{s=1}^{N} \mathbb{1}[s \in S] f_{os}^X,$$

where $\Phi_{ok}(S,\varphi) = \sum_{s\in S} (T_s/w_s)^\theta (d_{os}(\varphi)\tau_{sk})^{-\theta}$ is the production potential of the firm.

Define the marginal benefit of adding an establishment in location s by

$$D\pi_o(s;S,\varphi,z) \equiv \pi_o(S \cup \{s\},\varphi,z) - \pi_o(S \setminus \{s\},\varphi,z)$$
$$= \frac{\sigma^{-\sigma}}{(\sigma-1)^{1-\sigma}} \tilde{\Gamma} \left(\frac{z}{h(\varphi)}\right)^{\sigma-1} \sum_k E_k P_k^{\sigma-1} \left[\Phi_{ok}(S \cup \{s\},\varphi)^{\frac{\sigma-1}{\theta}} - \Phi_{ok}(S \setminus \{s\},\varphi)^{\frac{\sigma-1}{\theta}}\right] - f_{os}^X$$

The goal is to show that a sufficient condition for the single crossing differences condition holds: the marginal benefit $D\pi_o(s;S,\varphi,z)$ changes monotonically as S increases.

Let $S_1 \subseteq S_2$ be given and neither includes location s. Since the fixed cost f_{os}^X is the same, the difference in the marginal benefit comes from the additional profit location s generates, which depends on the firm's other establishments. That is,

$$D\pi_o(s;S_1,\varphi,z) - D\pi_o(s;S_2,\varphi,z) = \frac{\sigma^{-\sigma}}{(\sigma-1)^{1-\sigma}} \tilde{\Gamma} \left(\frac{z}{h(\varphi)}\right)^{\sigma-1} \sum_k E_k P_k^{\sigma-1} \times$$
$$\left[\Phi_{ok}(S_1 \cup \{s\},\varphi)^{\frac{\sigma-1}{\theta}} - \Phi_{ok}(S_1,\varphi)^{\frac{\sigma-1}{\theta}} - \Phi_{ok}(S_2 \cup \{s\},\varphi)^{\frac{\sigma-1}{\theta}} + \Phi_{ok}(S_2,\varphi)^{\frac{\sigma-1}{\theta}}\right].$$

Denote $f(S) \equiv (\Phi_{ok}(S,\varphi))^{\frac{\sigma-1}{\theta}}$ and $\Delta f(S) \equiv f(S \cup \{s\}) - f(S)$. Here, I drop the other notations and keep only S for brevity. We would like to show either $\Delta f(S_1) \geq \Delta f(S_2)$ or $\Delta f(S_1) \leq \Delta f(S_2)$ where $S_1 \subseteq S_2$.

The relationship between $\Delta f(S_1)$ and $\Delta f(S_2)$ depends on the concavity of the function $f(S)$ and is determined by the sign of $\frac{\sigma-1}{\theta} - 1$. If $\frac{\sigma-1}{\theta} - 1 < 0$, $f(S)$ is concave. Thus, $\Delta f(S_1) \geq \Delta f(S_2)$, and the single crossing differences condition holds. In this case, the benefit of an additional location s decreases as the firm has more establishments in other locations, and a firm's establishments are substitutes. In the case where $\frac{\sigma-1}{\theta} - 1 > 0$, the single crossing differences condition still holds, while establishments will be complements.

Computation algorithm. The algorithm below is reminiscent of the single-agent squeezing procedure described in Arkolakis et al. (2023). For the sake of brevity, I focus on the case where establishments are substitutes. I drop the notation for the firm's fundamentals (i.e., headquarters o and productivity z) and ICT level φ and denote the set of all possible combinations as $\tilde{S}$. The algorithm proceeds as follows:

1. Evaluate the marginal value of adding an establishment s at the supremum and infimum of $\tilde{S}$, i.e., $D\pi(s; \sup(\tilde{S}))$ and $D\pi(s; \inf(\tilde{S}))$. I start with a vector indicating that the firm has establishments in all other locations as the supremum, and a vector indicating that the firm only has its headquarters as the infimum.

2. If $D\pi(s; \inf(\tilde{S})) < 0$, update $\tilde{S}$ to exclude s. If $D\pi(s; \sup(\tilde{S})) \geq 0$, update $\tilde{S}$ to include s. Otherwise, there is no update. This procedure is repeated until $\tilde{S}$ converges to a fixed point.

3. If $\tilde{S}$ converges to a singleton, then we have reached the optimal set of locations. Otherwise, split $\tilde{S}$ into two subsets and repeat Steps 1 and 2 on each subset. Then, the profit at local optima is evaluated to obtain the global optimum.

F Policy Simulation Appendix

F.1 Model Extension: Endogenous Wages

The baseline model assumes a perfectly elastic labor supply with exogenous wages. In this section, I incorporate endogenous wages by estimating an alternative model in which the labor supply is perfectly inelastic, as defined in Section C.4. Table E.3 presents the corresponding third-step estimates using the method of simulated moments.

Table F.1 shows the welfare changes, as measured by the ratio of wages to the local price index, for the Internet privatization and compares them to those of the baseline model. With endogenous wages, the national average welfare gain is 1.8%, which is slightly greater than the baseline estimate of 1.7%. I further decompose the welfare change into two components: changes in efficiency, measured by the inverse of the local price index, and changes in wages. Under the model with endogenous wages, the nationwide efficiency gain is 1.76%, accounting for half of the welfare increase compared to the baseline model. Additionally, wages rise by 5

F.2 Decomposing Local Efficiency Gains

To elucidate the various channels of efficiency gains, I decompose the local efficiency gains in each location into contributions from different types of firms, particularly local firms (i.e., firms headquartered in that location) and outside firms (i.e., firms headquartered in another location). For outside firms, I further divide them into four groups depending on whether they set up establishments in the location before and after the policy change: "stayers" denote outside firms that have establishments in the location both before and after the policy change; "entrants" and "exiters" denote outside firms that entered or exited the location afterward, respectively; and "nevercomers" denote outside firms that never have establishments in the location.

In each market k, define the price index of local firms by $P_k^{\text{local}} \equiv \left(\int_0^{m_k} p_{kk}(i)^{1-\sigma} di\right)^{\frac{1}{1-\sigma}}$, and for stayers as $P_k^{\text{stayers}} \equiv \left(\sum_{o\neq k} \int_0^{m_o} \mathbb{1}[k \in S^0(i), k \in S^1(i)]\, p_{ok}(i)^{1-\sigma} di\right)^{\frac{1}{1-\sigma}}$, where $S^0(i)$ and $S^1(i)$ are the set of establishment locations of firm i in the benchmark equilibrium and counterfactual equilibrium, respectively. Similarly, this applies to other types of firms.

We can decompose the welfare or efficiency gains from policy simulations into contributions from each type of firm.

Internet privatization. Table F.2 breaks down the efficiency gain in each census division into contributions from local firms and outside firms including stayers, entrants, exiters, and never-comers. Take the New England census division, for example. Stayers and entrants contribute 24% and 23%, respectively, whereas exiters reduce the local efficiency by 9% because of higher shipping costs. Those outside firms that never set up local establishments account for approximately 44% of the changes through trade, i.e., both the traditional trade channel from their headquarters and the third-location trade channel from their nonheadquarters establishments. In sum, outside firms account for four-fifths of the local efficiency gains. Local firms, in contrast, account for one-fifth of the local efficiency gains. The last row shows the average contribution from each type of firm. In total, stayers, entrants, and exiters account for over 50% of the local efficiency gains, underscoring the importance of multi-unit production across locations in determining local efficiency gains.

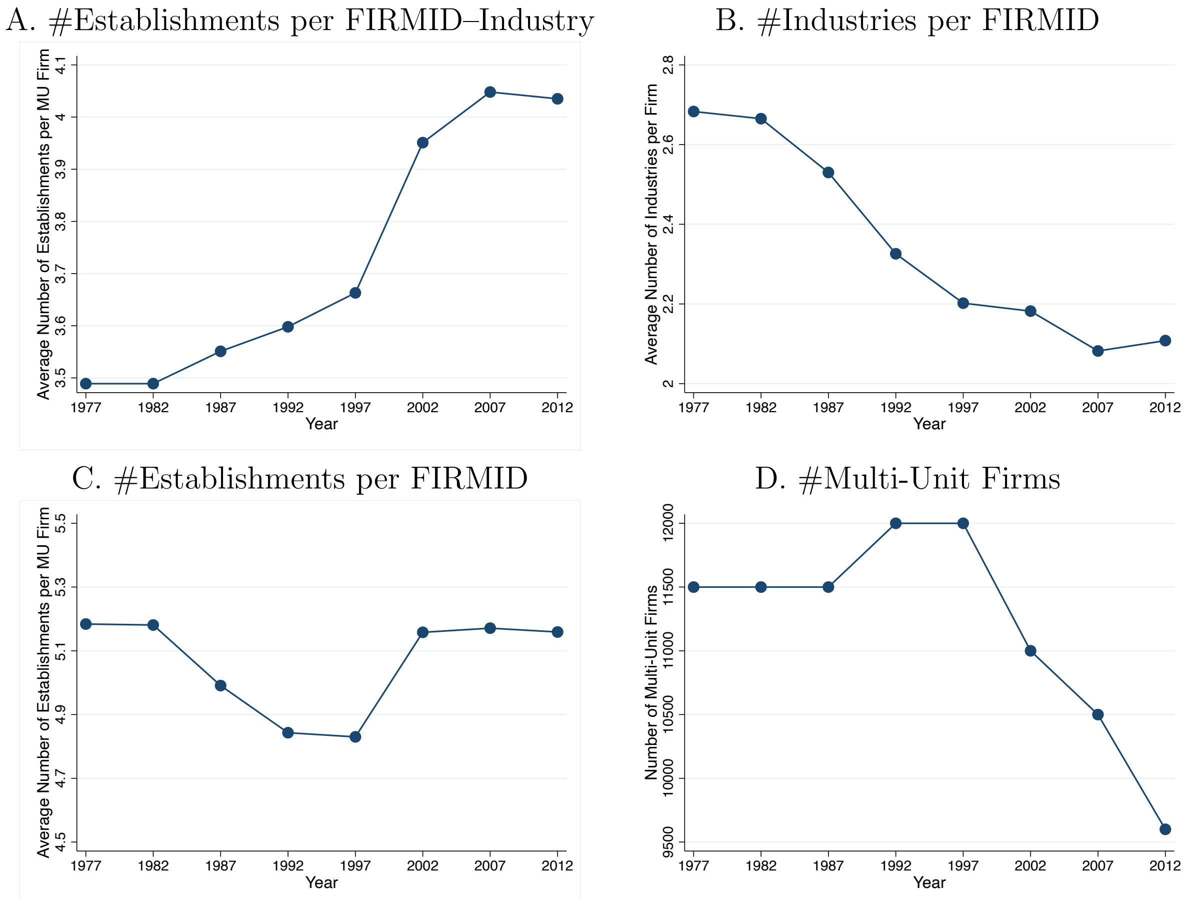
Local ICT cost reduction. Table F.3 shows how a local ICT cost reduction in the West South Central census division is transmitted to other locations. The efficiency gains in West South Central census division are driven primarily by the productivity increases of local firms, as the fixed costs of ICT adoption decrease. In other locations, however, efficiency gains are driven by outside firms. On average, stayers contribute to a 22% efficiency increase in the other locations, driven by the productivity increase of the incumbent establishments set up by multi-unit firms headquartered in the West South Central census division. The geographic expansion of firms from West South Central further enhances the positive spillover to other locations. This effect is reflected by the contribution from entrants, i.e., those West South Central firms that expand to other locations after ICT improvements, which accounts for approximately half of the efficiency change in the other census divisions, on average. Moreover, as markets become more competitive, firms from other locations contract, leading to a decline in efficiency. Exiters, i.e., those firms that exit the location as a result of the entry of more productive West South Central firms, have a negative impact, approximately −5% on average, on the efficiency of other locations. Never-comers contribute 41% of the efficiency changes, driven by spillover through trade.

The lower panel of Table F.3 reports the efficiency gains and the corresponding decomposition for each census division. Due to the heterogeneity in locations' initial shares of multi-unit firms and the expansion of West South Central firms, the contribution from each type of firm varies across locations. Nonetheless, multi-unit production, which includes stayers, entrants and exiters, is the most important determinant of the geographic distribution of efficiency gains.

National ICT cost reduction. Table F.4 presents the decomposition for the national ICT cost reduction. On the one hand, local firms' contribution is proportional to the extent of the local cost reduction. For example, the Mountain and Pacific census divisions, where the cost reduction is minimal, do not benefit from the efficiency gains of local firms. This is because local firms' ICT adoption decisions are not affected by changes in the fixed cost of adopting ICT. On the other hand, outside firms, especially stayers and entrants, play a significant role in determining local efficiency gains, accounting for more than half of the efficiency gains on average.

Additional Figures

Figure A.1: Span of Control for Multi-Unit Firms, Alternative Firm Definitions



Notes: These figures show the span of control for multi-unit firms in the manufacturing sector from the Longitudinal Business Database (LBD). Panel A plots the average number of establishments per firm, where each firm is a FIRMID×six-digit NAICS industry pair. Panel B–D define firm by the FIRMID. Panel B plots the average number of industries per firm of multi-unit firms. Panel C plots the average number of establishments per firm of multi-unit firms, including their establishments in multiple locations and multiple industries. Panel D plots the number of multi-unit firms. Multi-unit firms are firms with more than one establishment.

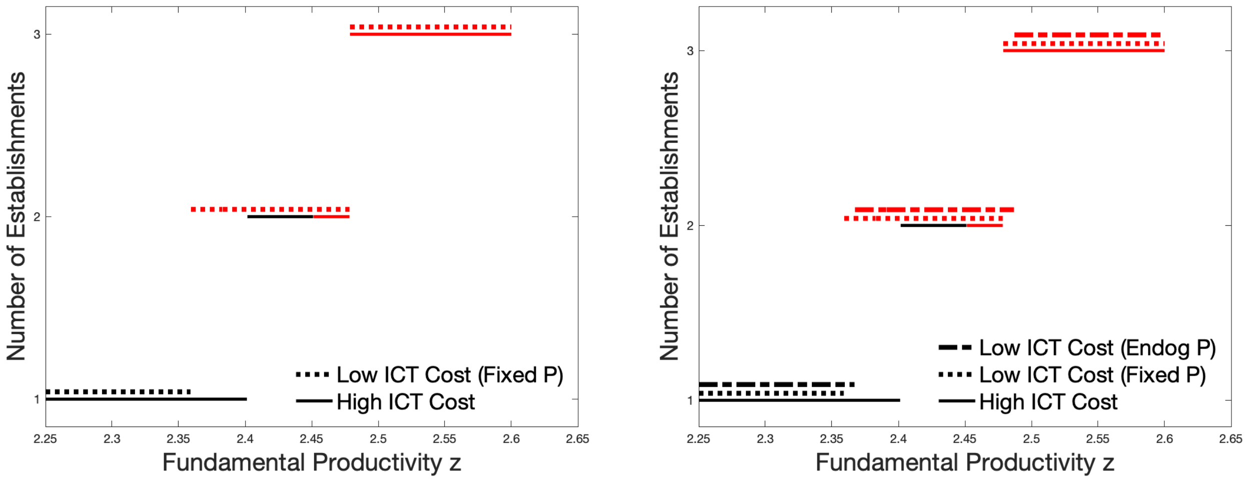
Figure B.1: Equilibrium Effects of an ICT Cost Reduction

A. Direct Effect

$\uparrow$ ICT adoption $\Rightarrow$ Expand

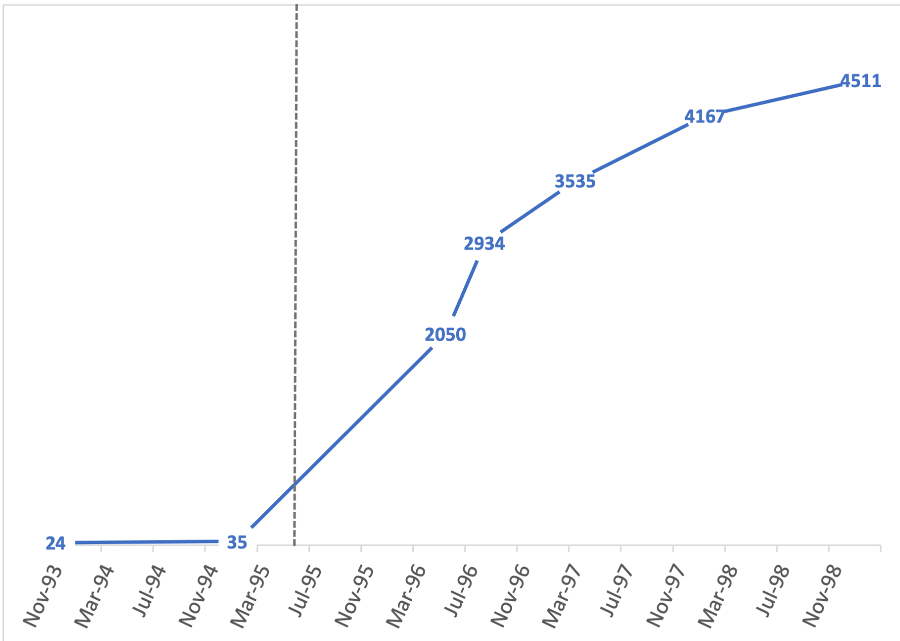
B. Indirect Effect

$\uparrow$ Market competition $\Rightarrow$ Contract



Notes: These figures plot the policy functions of location choices and ICT adoption against productivity in a simple example with three locations $\{HQ, L, H\}$ and for firms headquartered in HQ. Panel A plots the number of establishments and ICT adoption against productivity, with equilibrium prices held constant. The solid line corresponds to a high ICT cost, and the dotted line corresponds to a low ICT cost. The black fragment represents a low ICT level, and the red fragment represents a high ICT level. Panel B adds a dashed line that represents the policy function when prices are allowed to adjust endogenously.

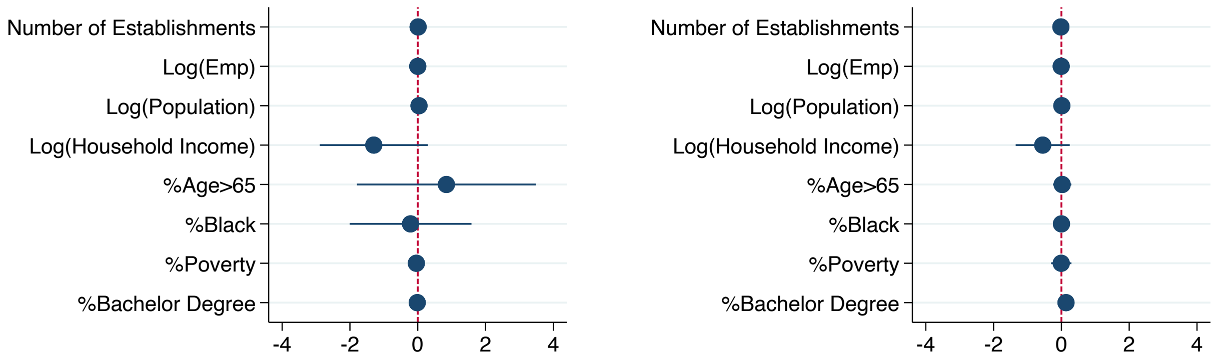
Figure C.1: Number of Internet Service Providers (ISPs) Listed in *Boardwatch Magazine*



Notes: This figure plots the number of Internet service providers listed in *Boardwatch Magazine* from November 1993 to January 1999. These numbers are documented in Table 5.1 in Greenstein (2015).

Figure C.2: Regression Estimates of the Distance to the Nearest NSFNET Node on Firm and County Characteristics

A. Level B. One-Year Growth Rate

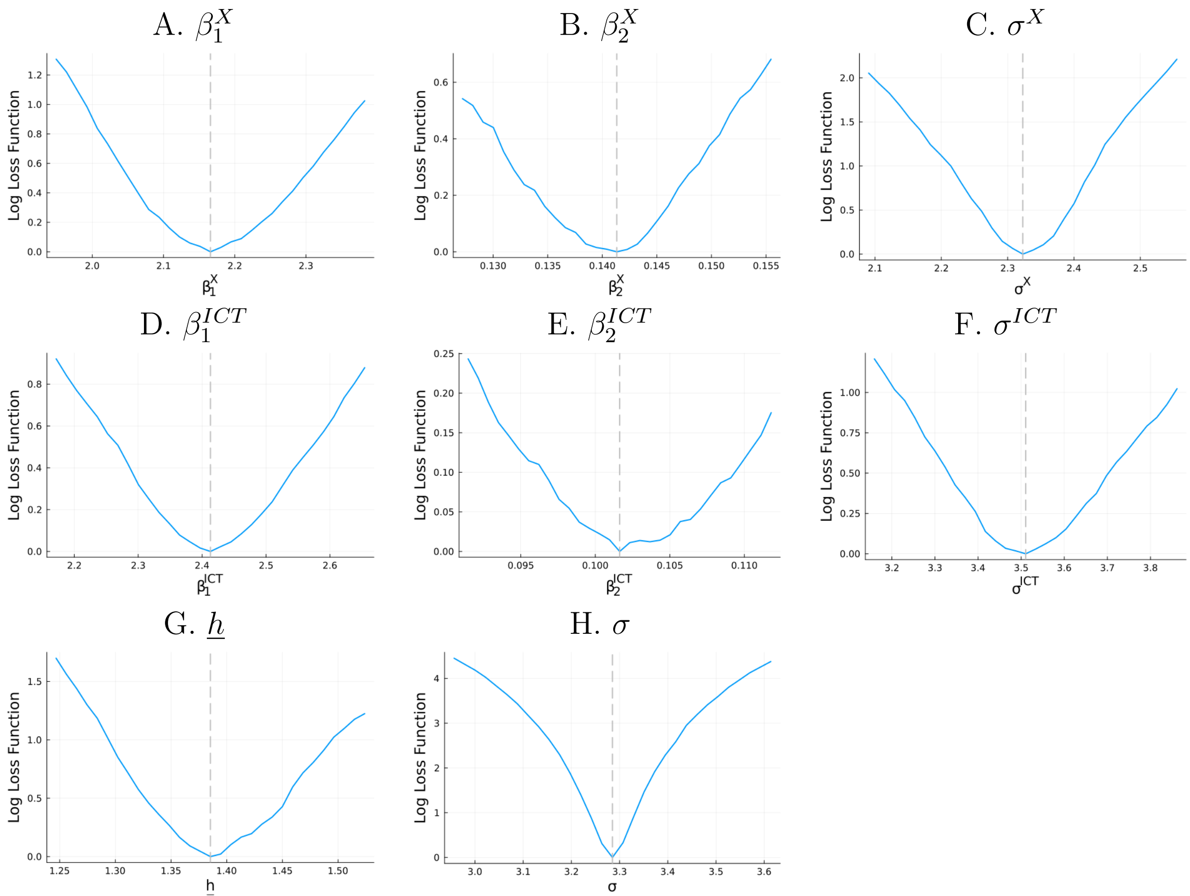


Notes: These figures plot the estimated coefficients of the following regression using observations from 1987:

$$\text{HQDistToNode}_i = \alpha + X_i\beta + \alpha_i^{\text{Industry}} + \alpha_i^{\text{State}} + u_i,$$

where the dependent variable is the distance from a firm's headquarters to the nearest NSFNET node, X_i includes the firm's number of establishments, logarithm of employment, county characteristics including the logarithm of the local population, logarithm of median household income, share of the population below the poverty line, share of the population over sixty-five years old, share of the Black population, and share of the population with a bachelor's degree and above, as well as one-year growth rates in these covariates. $\alpha_i^{\text{Industry}}$ is the 4-digit NAICS industry fixed effect, and α_i^{State} is the state fixed effect. Standard errors are clustered at the county level. Panels A and B plot the estimated coefficients on the level and one-year growth rate of the firm and county covariates, respectively.

Figure C.3: Loss Function from Structural Estimation



Notes: This graph displays the loss function against each parameter, with the other parameters held at the optimal values. The loss function is calculated by:

$$g(\phi) = [m - \hat{m}(\phi)]' W [m - \hat{m}(\phi)],$$

where the moments m include seven moments regarding firms' geographic expansion and ICT adoption. I use the identity matrix as the weighting matrix. In each panel, the vertical line indicates the estimated value.

Additional Tables

Table A.1: Summary Statistics of the 1999 Computer Network Use Supplement: Establishment Level

	N	Mean	S.D.
ICT Adoption			
Internet	35,000	0.743	0.437
Intranet	35,000	0.406	0.491
Electronic data interchange (EDI)	35,000	0.229	0.420
Extranet	35,000	0.061	0.239
Local area network (LAN)	35,000	0.687	0.464
Communication			
Within Firm	35,000	0.401	0.490
Customers	35,000	0.271	0.445
Suppliers	35,000	0.476	0.499

Notes: This table shows summary statistics of establishments in the Computer Network Use Supplement (CNUS) to the 1999 Annual Survey of Manufactures, including the establishment's ICT adoption and communication patterns. Each variable regarding ICT adoption is an indicator that is set to one if the establishment is connected to a type of network. Variables regarding communication are indicators that are set to one if the establishment communicates with other company units, external customers, and external suppliers.

Table A.2: Summary Statistics of the Longitudinal Business Database, Mfg., Census Years

	N	Mean	S.D.
Employment	2,311,000	53.8	428.2
Payroll (in thousands)	2,311,000	1759	23690
Multi-unit firm	2,311,000	0.039	0.193
Number of establishments	2,311,000	1.105	1.205

Notes: This table shows summary statistics of firms in the manufacturing sector from the Longitudinal Business Database with observations in census years from 1977 to 2012, i.e., years ending with 7 and 2. There are eight census years during this period. Each firm is a FIRMID×6-digit NAICS industry pair. Multi-unit firm is an indicator that is set to one if a firm has more than one establishment.

Table A.3: Summary Statistics of the Balanced Sample from 1987 to 2007

	N	Mean	S.D.
Employment	702,000	119.10	920.10
Payroll (in thousands)	702,000	4502	47010
Multi-unit firm	702,000	0.084	0.278
Number of establishments	702,000	1.340	2.354

Notes: This table shows summary statistics of the firms in the manufacturing sector from a balanced panel in the Longitudinal Business Database (LBD) from 1987 to 2007. There are twenty-one years during this period. Each firm is a FIRMID×six-digit NAICS industry pair. Multi-unit firm is an indicator that is set to one if a firm has more than one establishment.

Table B.1: Firms' ICT Adoption, Geographic Expansion, and Communication Patterns

	Growth Rate from 1997 to 2002 in	Communication		
	Number of Establishments	Within-Firm	Customer	Supplier
	(1)	(2)	(3)	(4)
Intranet	0.030***	0.259***	0.105***	0.056***
	(0.010)	(0.009)	(0.009)	(0.009)
EDI	0.002	0.045***	0.092***	0.112***
	(0.011)	(0.009)	(0.009)	(0.009)
Extranet	-0.000	0.104***	0.159***	0.068***
	(0.018)	(0.012)	(0.014)	(0.012)
Internet	0.012**	0.104***	0.129***	0.281***
	(0.006)	(0.006)	(0.007)	(0.008)
LAN	0.009	0.076***	0.061***	0.148***
	(0.006)	(0.007)	(0.007)	(0.008)
N	16500	18500	18500	18500
Avg. dep. var.	0.047	0.338	0.294	0.533
R^2	0.025	0.369	0.227	0.268
Firm controls	Y	Y	Y	Y
Industry FE	Y	Y	Y	Y
State FE	Y	Y	Y	Y

Notes: This table presents the relationship between firms' ICT adoption and their geographic expansion and communication patterns. Columns (1) uses the matched sample from the Longitudinal Business Database (LBD) and the Computer Network Use Supplement (CNUS) and estimates a regression of the form:

$$\Delta Y_{i,97-02} = \alpha + \beta_1 \text{Intranet}_{i,99} + \beta_2 \text{EDI}_{i,99} + \beta_3 \text{Extranet}_{i,99} + \beta_4 \text{Internet}_{i,99} + \beta_5 \text{LAN}_{i,99} + X_{i,97}\gamma + \varepsilon_{i,97-02},$$

where the dependent variable $\Delta Y_{i,97-02}$ is the growth rate of firm i in the number of establishments from 1997 to 2002 ($\Delta Y_{i,97-02} = \log Y_{i,02} - \log Y_{i,97}$). The independent variables include indicators set to one if firm i adopted intranet, electronic data interchange (EDI), extranet, Internet, or local area network (LAN) by 1999, and $X_{i,97}$ is a vector of the firm's initial characteristics in 1997, including the logarithm of employment, firm age fixed effect, state fixed effect, and industry fixed effect at the four-digit NAICS level. Column (1) uses firms in the CNUS sample that are matched with the 1997 and 2002 LBD.

Columns (2)–(4) use the CNUS sample and estimate a regression of the form:

$$Y_{i,99} = \alpha + \beta_1 \text{Intranet}_{i,99} + \beta_2 \text{EDI}_{i,99} + \beta_3 \text{Extranet}_{i,99} + \beta_4 \text{Internet}_{i,99} + \beta_5 \text{LAN}_{i,99} + X_{i,99}\gamma + \varepsilon_{i,99},$$

where the dependent variables are indicators set to one if any establishment of the firm provides information to other company units, external customers, and external suppliers. $X_{i,99}$ is a vector of firm characteristics in 1999, including the logarithm of capital to labor ratio, logarithm of employment, skill mix measured by the ratio of nonproduction workers to production workers, firm age fixed effect, state fixed effect, and industry fixed effect at the four-digit NAICS level. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table B.2: Robustness Check of Firms' ICT Adoption and Expansion

Dep. Var:	FIRMID–Industry		FIRMID		
Growth Rate	#Establishments in Mfg. Sector		#Establishments	Employment	%Employment
during 1997–2002 in	Baseline (1)	Single-Industry Firms (2)	in All Sectors (3)	in All Sectors (4)	in Mfg. Sector (5)
Intranet	0.030***	0.022**	0.091***	0.168***	0.079
	(0.010)	(0.009)	(0.025)	(0.023)	(0.055)
EDI	0.002	-0.012	0.047*	0.046**	0.077
	(0.011)	(0.008)	(0.027)	(0.018)	(0.067)
Extranet	-0.000	0.019	0.086*	0.076***	-0.018
	(0.018)	(0.020)	(0.047)	(0.026)	(0.027)
Internet	0.012**	0.007*	0.011	0.036**	0.003
	(0.006)	(0.004)	(0.010)	(0.017)	(0.008)
LAN	0.009	0.001	0.026**	0.128***	0.027
	(0.006)	(0.004)	(0.013)	(0.018)	(0.019)
N	16500	13000	16500	16500	16500
Avg. dep. var.	0.047	0.018	0.102	0.084	0.019
R^2	0.025	0.023	0.024	0.062	0.007
Firm controls	Y	Y	Y	Y	Y
Industry FE	Y	Y	Y	Y	Y
State FE	Y	Y	Y	Y	Y

Notes: This table estimates regressions of the form:

$$\Delta Y_{i,97-02} = \alpha + \beta_1 \text{Intranet}_{i,99} + \beta_2 \text{EDI}_{i,99} + \beta_3 \text{Extranet}_{i,99} + \beta_4 \text{Internet}_{i,99} + \beta_5 \text{LAN}_{i,99} + X_{i,97}\gamma + \varepsilon_{i,97-02},$$

where $\Delta Y_{i,97-02}$ is the growth rate of firm i in an outcome Y_i from 1997 to 2002 ($\Delta Y_{i,97-02} = \log Y_{i,02} - \log Y_{i,97}$). The independent variables include indicators set to one if firm i adopted intranet, electronic data interchange (EDI), extranet, Internet, or local area network (LAN) by 1999. X_i is a vector of the firm's initial characteristics in 1997, including the logarithm of employment, firm age fixed effect, state fixed effect, and industry fixed effect at the four-digit NAICS Level. The dependent variable in Column (1) is the five-year growth rate in the number of establishments per six-digit NAICS industry associated with a unique FIRMID. Column (2) is restricted to firms that operate in a single industry throughout the period. The dependent variable in Column (3) is the five-year growth rate in the number of establishments that firm i has, where we identify a firm by the unique FIRMID and consider the firm's establishments in all sectors. The dependent variables in Columns (4)–(5) are the five-year growth rates in the firm's total employment in all sectors and the firm's employment share in the manufacturing sector, respectively. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table B.3: Establishments' ICT Adoption and Communication Patterns

	Communication					
	Within Firm		With Customers		With Suppliers	
	(1)	(2)	(3)	(4)	(5)	(6)
Intranet	0.247***	0.157***	0.067***	0.050***	−0.004	0.034***
	(0.007)	(0.011)	(0.006)	(0.010)	(0.007)	(0.010)
EDI	0.047***	0.068***	0.098***	0.116***	0.139***	0.137***
	(0.007)	(0.010)	(0.007)	(0.010)	(0.007)	(0.010)
Extranet	0.097***	0.061***	0.134***	0.105***	0.100***	0.105***
	(0.012)	(0.015)	(0.013)	(0.016)	(0.012)	(0.016)
Internet	0.105***	0.135***	0.115***	0.083***	0.238***	0.145***
	(0.006)	(0.014)	(0.005)	(0.010)	(0.007)	(0.013)
LAN	0.085***	0.064***	0.057***	0.037***	0.111***	0.057***
	(0.006)	(0.011)	(0.006)	(0.011)	(0.006)	(0.011)
N	35000	18000	35000	18000	35000	18000
R^2	0.226	0.303	0.137	0.308	0.189	0.351
Estab controls	Y	Y	Y	Y	Y	Y
Industry FE	Y	Y	Y	Y	Y	Y
State FE	Y	Y	Y	Y	Y	Y
Firm FE		Y		Y		Y

Notes: This table uses establishment-level data from the CNUS sample and estimates regressions of the form:

$$Y_{i,99} = \alpha + \beta_1 \text{Intranet}_{i,99} + \beta_2 \text{EDI}_{i,99} + \beta_3 \text{Extranet}_{i,99} + \beta_4 \text{Internet}_{i,99} + \beta_5 \text{LAN}_{i,99} + X_{i,99}\gamma + \varepsilon_{i,99},$$

where the dependent variables are indicators set to one if an establishment i provides information to other company units (Columns (1)–(2)), external customers (columns (3)–(4)), and external suppliers (Columns (5)–(6)). The independent variables include indicators set to one if establishment i adopted intranet, electronic data interchange (EDI), Extranet, Internet, and local area network (LAN) by 1999. $X_{i,99}$ is a vector of establishment characteristics in 1999, including the logarithm of capital to labor ratio, logarithm of employment, skill mix measured by the ratio of nonproduction workers to production workers, age fixed effect, state fixed effect, and industry fixed effect at the four-digit NAICS level. Columns (2), (4), and (6) further include the firm fixed effect. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table D.1: Estimates of the Effect of ICT on Firms' Expansion: Robustness

	County Controls (1)	Different SE Clustering (2)	Excl. Univ. Towns (3)
HQDistToNode × Post	-0.323***	-0.323***	-0.400***
	(0.097)	(0.102)	(0.116)
N	702000	702000	429000
Avg. Dep. Var	5.016	5.016	5.230
R^2	0.899	0.899	0.900
County Controls	Y	Y	Y
Industry-Year FE	Y	Y	Y
State-Year FE	Y	Y	Y

Notes: This table estimates regressions of the form:

$$Y_{it} = \alpha_i + \beta \text{HQDistToNode}_i \times \text{Post}_t + \text{CountyControls}_{it}\gamma + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it},$$

where the dependent variable is the number of establishments firm i operates in year t. α_i is the firm fixed effect, HQDistToNode_i is the distance from the ZIP code in which firm i is headquartered to its nearest NSFNET node (in 100 miles), Post_t is an indicator set to one for years after 1995, and $\text{CountyControls}_{it}$ is a vector of county characteristics, including the logarithm of population and median household income, share of the Black population and people over 65 years old, and share of adults with a bachelor's degree. $\alpha_i^{\text{Industry-Year}}$ and $\alpha_i^{\text{State-Year}}$ are industry–year and state–year fixed effects, respectively. The regressions are weighted by the firm's employment share. Standard errors are clustered at the firm and headquarters county level in Columns (1) and (3), and at the firm and headquarters state level in column (2). Column (3) excludes firms headquartered within 250 miles from the nodes that are university towns, including Princeton, Champaign, Ithaca, Palo Alto, Ann Arbor, College Park, and Cambridge. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table D.2: Estimates of the Effect of ICT on Firms' Expansion: Employment

	Log(Emp) (1)	Log(Emp/Establishment) (2)	Log(Wage) (3)
HQDistToNode × Post	-0.019*	-0.001	-0.004
	(0.011)	(0.011)	(0.004)
N	702000	702000	702000
Avg. Dep. Var	6.123	5.090	3.383
R^2	0.973	0.957	0.837
County Controls	Y	Y	Y
Industry-Year FE	Y	Y	Y
State-Year FE	Y	Y	Y

Notes: This table estimates regressions of the form:

$$Y_{it} = \alpha_i + \beta \text{HQDistToNode}_i \times \text{Post}_t + \text{CountyControls}_{it}\gamma + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it},$$

where the dependent variables are the logarithm of employment of firm i in year t, the logarithm of employment per establishment, and the logarithm of average wage rate of the firm, as shown in Columns (1)–(3). α_i is the firm fixed effect, HQDistToNode_i is the distance from the ZIP code in which firm i is headquartered to its nearest NSFNET node (in 100 miles), Post_t is an indicator set to one for years after 1995, and $\text{CountyControls}_{it}$ is a vector of county characteristics, including the logarithm of population and median household income, share of the Black population and people over 65 years old, and share of adults with a bachelor's degree. $\alpha_i^{\text{Industry-Year}}$ and $\alpha_i^{\text{State-Year}}$ are industry–year and state–year fixed effects, respectively. The regressions are weighted by the firm's employment share. Standard errors are clustered at the firm and headquarters county level. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table D.3: Estimates of the Effect of ICT on Firms' Expansion: Location of New Establishments

	$\overline{\text{DistToNode}}^{\text{New}}$	$\overline{\text{Log(Pop)}}^{\text{New}}$	$\overline{\text{Log(HH Income)}}^{\text{New}}$	$\overline{\text{\%Poverty}}^{\text{New}}$
	(1)	(2)	(3)	(4)
HQDistToNode × Post	0.315**	-0.318	-0.087***	-0.001
	(0.136)	(0.259)	(0.027)	(0.006)
N	1200	1200	1200	1200
Avg. Dep. Var	1.574	12.36	10.47	0.127
County Controls	Y	Y	Y	Y
Industry-Year FE	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y
	$\overline{\text{\%Black}}^{\text{New}}$	$\overline{\text{\%Age>65}}^{\text{New}}$	$\overline{\text{\%Bachelor's Degree}}^{\text{New}}$	
	(5)	(6)	(7)	
HQDistToNode × Post	-0.025	0.019***	-0.019	
	(0.016)	(0.005)	(0.012)	
N	1200	1200	1200	
Avg. Dep. Var	0.123	0.125	0.206	
County Controls	Y	Y	Y	
Industry-Year FE	Y	Y	Y	
State-Year FE	Y	Y	Y	

Notes: This table estimates regressions of the form:

$$Y_{it} = \alpha_i + \beta \text{HQDistToNode}_i \times \text{Post}_t + \text{CountyControls}_{it}\gamma + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it},$$

where the dependent variable is a characteristic of the new establishments of firm i in year t, α_i is the firm fixed effect, HQDistToNode_i is the distance from the ZIP code in which firm i is headquartered to its nearest NSFNET node (in 100 miles), Post_t is an indicator set to one for years after 1995, and $\text{CountyControls}_{it}$ is a vector of county characteristics, including the logarithm of population and median household income, shares of the Black population and people over 65 years old, and share of adults with a bachelor's degree. $\alpha_i^{\text{Industry-Year}}$ and $\alpha_i^{\text{State-Year}}$ are industry–year and state–year fixed effects, respectively. The dependent variable is the average distance from the new establishments to their nearest NSFNET node for Column (1). The dependent variables for Columns (2)–(7) are the average population, household income, poverty rate, shares of the black population and people over 65 years old, and share of adults with a bachelor's degree of the counties where new establishments are located. The regressions are weighted by the firm's employment share. Standard errors are clustered at the firm and headquarters county level. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table D.4: Estimated Effects of Internet Privatization on Firms' Geographic Expansion: By Industry Shipping Costs

	Industries with	
	High Shipping Costs	Low Shipping Costs
	(1)	(2)
HQDistToNode × Post	-0.440***	-0.115
	(0.140)	(0.078)
N	429000	273000
Avg. Dep. Var	5.942	3.874
R^2	0.906	0.866
County controls	Y	Y
Industry-Year FE	Y	Y
State-Year FE	Y	Y

Notes: This table estimates regressions of the form:

$$Y_{it} = \alpha_i + \beta \text{HQDistToNode}_i \times \text{Post}_t + \text{CountyControls}_{it}\gamma + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it},$$

where the dependent variable is the number of establishments firm i operates in year t. α_i is the firm fixed effect, HQDistToNode_i is the distance from the ZIP code in which firm i is headquartered to its nearest NSFNET node (in 100 miles), Post_t is an indicator set to one for years after 1995, and $\text{CountyControls}_{it}$ is a vector of county characteristics, including the logarithm of population and median household income, share of the Black population and people over 65 years old, and share of adults with a bachelor's degree. $\alpha_i^{\text{Industry-Year}}$ and $\alpha_i^{\text{State-Year}}$ are industry–year and state–year fixed effects, respectively. The regressions are weighted by the firm's employment share. Industries are categorized by their shipping costs, measured by the average shipping distance from the 2012 Commodity Flow Survey. Column (1) and (2) are restricted to industries with high and low shipping costs, respectively. Standard errors are clustered at the firm and headquarters county level. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table D.5: Estimated Effects of the Internet Privatization on Firms' ICT Adoption

	Intranet (1)	Internet (2)	Extranet (3)	EDI (4)
HQDistToNode × Post	-0.035***	0.045**	-0.001	-0.020**
	(0.009)	(0.019)	(0.010)	(0.008)
N	58000	58000	58000	58000
Avg. Dep. Var	0.036	0.220	0.009	0.035
County Controls	Y	Y	Y	Y
Industry-Year FE	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y

Notes: This table estimates regressions of the form:

$$Y_{it} = \alpha_i + \beta \text{HQDistToNode}_i \times \text{Post}_t + \text{CountyControls}_{it}\gamma + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it},$$

where the dependent variable is a time-varying indicator of a firm's network status that interacts the firm's network adoption in 1999 and a postprivatization indicator. The dependent variables in Columns (1)–(4) are the firm's adoption of intranet, Internet, extranet, and electronic data interchange (EDI). α_i is the firm fixed effect, HQDistToNode_i is the distance from the ZIP code in which firm i is headquartered to its nearest NSFNET node (in 100 miles), Post_t is an indicator set to one for years after 1995, and $\text{CountyControls}_{it}$ is a vector of county characteristics, including the logarithm of population and median household income, shares of the Black population and people over 65 years old, and share of adults with a bachelor's degree. $\alpha_i^{\text{Industry-Year}}$ and $\alpha_i^{\text{State-Year}}$ are industry–year and state–year fixed effects, respectively. Standard errors are clustered at the firm and headquarters county level. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table E.1: Estimates of Census Division Fixed Effects and the State of Technology in 1999

	Census Division Fixed Effect		State of Technology
	Raw Estimates	Purified Estimates	
	(1)	(2)	(3)
New England	1.000	1.000	1.000
Middle Atlantic	2.721	1.620	0.985
East North Central	5.948	3.935	1.176
West North Central	2.314	0.695	0.807
South Atlantic	5.613	1.650	0.903
East South Central	2.166	0.536	0.793
West South Central	2.872	1.463	0.971
Mountain	1.537	0.700	0.878
Pacific	4.015	4.322	1.216

Notes: Column (1) reports the 1999 census division fixed effects estimated from the first-stage regression. Column (2) reports the purified fixed effects that are adjusted by the local wage of manufacturers. Column (3) reports the second-stage estimates of the 1999 census divisions' state of technology, i.e., the scale parameter of the Fréchet distribution for each census division. The shape parameter is set to 3.6. The estimated fixed effects and state of technology are normalized to those of the New England census division.

Table E.2: Average Fixed Costs of Setting Up Establishments and Adopting ICT

	Average Fixed Costs (in Millions USD)	
Census Division	Setting Up Establishments (Establishment Location)	Adopting ICT (Headquarters Location)
New England	3.53	2.17
Middle Atlantic	4.86	2.29
East North Central	4.68	2.22
West North Central	4.12	2.09
South Atlantic	6.69	2.24
East South Central	4.10	2.22
West South Central	5.83	2.22
Mountain	3.87	1.97
Pacific	6.21	1.98

Notes: This table reports the estimated average monetary value of the fixed costs in each census division. Column (1) shows the average costs of setting up establishments in each census division for firms with establishments in multiple census divisions. Column (2) shows the average costs of adopting ICT in the firms' headquarters census divisions for firms that adopt ICT. These costs are calculated with the assumption that the ratio of average sales to the fixed costs from the model is the same as that in data.

Table E.3: Estimates from the Method of Simulated Moments: Endogenous Wages

Parameter	Description	Value
σ	Demand elasticity across firms	3.280
$\underline{h}$	Firm-wide communication costs with low ICT	1.429
β_1^X	Intercept of avg. fixed costs of setting up establishments	2.251
β_2^X	Elasticity of avg. fixed costs of setting up establishments w.r.t distance	0.097
σ^X	Dispersion of fixed costs of setting up establishments	2.426
β_1^{ICT}	Intercept of avg. fixed costs of adopting ICT	2.371
β_2^{ICT}	Elasticity of avg. fixed costs of adopting ICT w.r.t. DistToNode	0.115
σ^{ICT}	Dispersion of fixed costs of adopting ICT	3.513

Notes: This table shows the third-step estimates with endogenous wages.

Table F.1: Gains from Internet Privatization: Endogenous Wages

	Baseline	Endogenous Wages		
%Change in	Efficiency	Efficiency	Wages	Welfare
National Average	1.69	1.76	0.05	1.80
New England	1.63	1.74	0.01	1.75
Middle Atlantic	1.72	1.77	0.10	1.87
East North Central	1.71	1.74	0.04	1.79
West North Central	1.70	1.74	0.09	1.83
South Atlantic	1.74	1.77	0.10	1.87
East South Central	1.65	1.67	-0.04	1.63
West South Central	1.48	1.69	-0.12	1.56
Mountain	1.62	1.78	0.13	1.91
Pacific	1.79	1.81	0.05	1.86

Notes: This table shows changes in efficiency, wages, and welfare with endogenous wages from the Internet privatization. Efficiency is measured by the inverse of local price index. Welfare is measured by the ratio of wage to local price index.

Table F.2: Decomposing of Efficiency Gains: Internet Privatization

	%Change in Efficiency	Decomposition (%)				
		Outside Firms				Local Firms
		Stayers	Entrants	Exiters	Never-Comers	
	(1)	(2)	(3)	(4)	(5)	(6)
New England	1.63	24	23	-9	44	18
Middle Atlantic	1.72	23	31	-7	23	30
East North Central	1.71	27	31	-7	13	36
West North Central	1.70	25	31	-7	36	14
South Atlantic	1.74	42	28	-10	18	21
East South Central	1.65	26	32	-9	42	10
West South Central	1.48	31	27	-13	34	20
Mountain	1.62	23	50	-22	39	10
Pacific	1.79	37	32	-8	13	25
National Average	1.69	29	32	-10	29	21

Notes: This table shows the efficiency gains in each census division from the Internet privatization and decomposes these gains to contributions from different types of firms. The efficiency gain is calculated as the change in the local price index. Column (1) shows the local efficiency gains in each census division. Columns (2)–(5) report the contribution to local efficiency gains from different outside firms, as described in Section F.2. Column (6) reports the contribution from local firms that are headquartered in each location.

Table F.3: Decomposing Efficiency Gains: Local ICT Cost Reduction

	%Change in Efficiency	Decomposition (%)				
		Outside Firms				Local Firms
		Stayers	Entrants	Exiters	Never-Comers	
	(1)	(2)	(3)	(4)	(5)	(6)
West South Central	0.030	-0	-0	-9	-2	110
Other Census Divisions	0.011	22	43	-5	41	-1
New England	0.012	1	57	-0	42	-0
Middle Atlantic	0.009	4	45	-1	51	-0
East North Central	0.011	29	69	-18	20	-0
West North Central	0.013	23	26	-2	54	-0
South Atlantic	0.012	55	25	-0	25	-5
East South Central	0.010	9	29	-14	77	-1
Mountain	0.017	8	63	-0	33	-4
Pacific	0.012	47	33	-5	26	-0
National Average	0.013	20	39	-6	36	11

Notes: This table shows the efficiency gains in each census division with a reduction in the fixed costs of ICT adoption in the West South Central census division and decomposes these gains to the contributions from different types of firms. The efficiency gain is calculated as the change in the local price index. Column (1) shows the local efficiency gains in each census division. Columns (2)–(5) report the contribution to local efficiency gains from different outside firms, as described in Section F.2. Column (6) reports the contribution from local firms that are headquartered in each location.

Table F.4: Decomposing of Efficiency Gains: National ICT Cost Reduction

	%Change in Efficiency	Decomposition (%)				
		Outside Firms				Local Firms
		Stayers	Entrants	Exiters	Never-Comers	
	(1)	(2)	(3)	(4)	(5)	(6)
New England	0.029	-0	17	-0	45	38
Middle Atlantic	0.031	31	11	-1	19	41
East North Central	0.023	28	30	-7	19	30
West North Central	0.023	35	9	-1	43	13
South Atlantic	0.032	18	45	-3	14	27
East South Central	0.023	18	25	-8	53	11
West South Central	0.018	12	36	-14	50	17
Mountain	0.028	34	33	-0	32	0
Pacific	0.022	41	41	-3	22	-0
National Average	0.026	24	28	-4	33	20

Notes: This table shows the efficiency gains in each census division with the national ICT cost reduction and decomposes these gains to the contributions from different types of firms. The efficiency gain is calculated as the change in the local price index. Column (1) shows the local efficiency gains in each census division. Columns (2)–(5) report the contribution to local efficiency gains from different outside firms, as described in Section F.2. Column (6) reports the contribution from local firms that are headquartered in each location.