Information and Communication Technology and Firm Geographic Expansion [*]

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Abstract

This paper studies how information and communication technology (ICT) affects the firm geographic organization and its implications on aggregate efficiency. ICT can widen firms' geographic span of control by reducing their internal communication costs. Empirical evidence from confidential US Census data shows that firms with more advanced technology have both higher within-firm communication and larger geographic coverage. I then develop a quantitative spatial equilibrium model in which firms endogenously adopt ICT, choose multiple production locations, and trade domestically. I estimate the model by exploiting natural experimental variation from the Internet privatization of the early 1990s. The model quantifies that privatization led to an overall efficiency gain of 1.3%, two-fifths of which came from firm geographic expansion. The distribution of these gains across locations is shaped by multi-unit firms' location choices. Policy simulations show that, in reducing the digital gap, a coordinated national policy leads to larger efficiency gains than local policies.

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

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1 Introduction

Information and communication technology (ICT) has improved dramatically in the past three decades. On the premise that ICT produces sizable benefits, investment in ICT amounts to 30% of the US nonresidential investment and governments worldwide have launched a multitude of initiatives aimed at enhancing ICT infrastructure.[1] This paper studies a novel source of efficiency gains from ICT: firms' geographic expansion. I show empirically and quantitatively that by improving within-firm communication for firms that operate in multiple locations (i.e., multi-unit firms), ICT widens their geographic span of control, leading to extensive efficiency gains across locations.

Understanding how multi-unit firms' geographic footprints respond to ICT improvements is crucial to assess the implications of ICT growth and policies that broaden ICT access. First, US multi-unit firms account for a large share of economic activities. Moreover, as shown in Figure 1, these firms have experienced significant expansion since the 1980s, and this expansion was particularly large during the mid-1990s and early 2000s when ICT—especially Internet-enabled technology—underwent rapid development. Finally, due to their wide coverage across locations, we need to account for geographic spillovers through multi-unit firms when assessing the impacts of ICT infrastructure projects.

In this paper, I develop and estimate a spatial equilibrium model of heterogeneous firms to quantify the importance of firms' geographic expansion in enhancing efficiency. The model allows firms to endogenously adopt ICT, choose multiple production locations, and trade domestically. ICT improves firm production efficiency by two channels: increasing firm-wide productivity and reducing internal communication costs between firms' headquarters and production sites, which allows firms to expand and locate closer to markets. Through geographic expansion, local ICT improvements affect not only the local establishments but also the multi-unit firms' establishments elsewhere, resulting in efficiency gains across different locations.

My analysis leverages confidential US Census data with establishment-level ownership linkages and locations, which allows me to construct firms' geographic footprints. I further augment this dataset with Census surveys of Computer Network Use that provide rich information on the establishment's network adoption and communication patterns.

I begin by presenting two motivating facts that link firms' ICT usage, their internal communication, and their geographic expansion. First, firms that have adopted an *intranet*, which reduces the cost of internal communication costs, experience larger growth rates in their geographic span of control. Second, intranet adoption increases the likelihood of within-firm communication using

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[1] Bureau of Economic Analysis (BEA) reports private fixed investment in structures, equipment, and intellectual properties by type: Table 5.4.5, 5.5.5, and 5.6.5 from `https://apps.bea.gov/iTable/?reqid=19&step=2&isuri=1&categories=survey`. Investments in ICT include communication structure, information processing equipment, and software.

online networks, which further corroborates the role of declining internal communication costs in firms' geographic expansion.

Motivated by these empirical findings, I then propose a spatial equilibrium model of firm ICT adoption and location choices to quantify efficiency gains from ICT improvements and to conduct policy simulations. In the model, firms choose a set of locations to open establishments, but communicating among their establishments is costly. Firms can adopt advanced ICT, which reduces communication costs and enhances production efficiency in two ways. First, ICT improves firm-wide productivity, affecting all its establishments equally. Second, it reduces headquarters–establishment communication costs that increase in distance. Notably, the second channel gives rise to rich interaction between ICT adoption and firm internal geography, as the benefit from ICT depends on firm's headquarters, the set of other establishment locations, and their proximity to markets.

Adopting ICT affects firm geography both on intensive and extensive margins. On the intensive margin, ICT adoption disproportionally benefits remote establishments, leading to the firm allocating more sales and labor there. On the extensive margin, it allows for geographic expansion. Importantly, ICT adoption and geographic expansion are complements. The benefit of expanding to more locations is higher if a firm adopts ICT; the benefit of adopting ICT is also higher for a firm with a larger geographic span of control. In equilibrium, reducing the cost of ICT has two countervailing effects: it increases the likelihood of adoption, which facilitates expansion, but it also intensifies market competition as more firms adopt ICT, which mitigates expansion. The net effect determines the geographic footprints of firms, which in turn shapes the distribution of efficiency gains from ICT adoption across locations.

I estimate the model to perform quantitative analyses. Key parameters concern the extent to which ICT improves firm-wide productivity, and to which it reduces communication costs between headquarters and establishments. I first quantify the latter channel by using establishment-level data from the US Census to estimate a within-firm labor allocation equation derived from the model. The idea is that, for firms with advanced ICT, the rate of decline in establishment size over distance is slower compared to those without such technology. To account for the endogeneity of firms' ICT adoption, I exploit quasi-experimental variation from one of the largest developments in US Internet history: the Internet privatization of 1995, a significant reduction in the costs of accessing high-speed Internet and adopting Internet-enabled applications.[2] Specifically, I instrument firms' ICT 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 so that nearby firms were able to quickly benefit from the privatization.[3]

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

[3] As the construction and installation of circuits constitute major costs for Internet service providers, Internet access would be cheaper for locations with better infrastructure. The locations of Internet backbone nodes

Indeed, firms with similar characteristics but were headquartered closer to the nodes were more likely to adopt advanced ICT at the time. Those firms were also more likely to expand after the Internet privatization, especially towards locations near the nodes, consistent with the model's extensive-margin implication on geographic expansion.

The estimates confirm that within-firm communication costs increase in distance. Adoption of ICT reduces the elasticity of communication costs with respect to distance by 50 percent. Nevertheless, this elasticity is lower than that of trade costs even for firms with low ICT, suggesting that local shocks can spill over more quickly to other locations through multi-unit firms.

To quantify the productivity improvement channel, I then use the method of simulated moments (MSM) to jointly estimate the firm productivity increase associated with ICT adoption, the fixed costs of adopting ICT, and the fixed costs of setting up establishments. The main computation challenge is to determine the firm's optimal set of locations, as the number of potential combinations increases exponentially as the number of locations rises. To overcome this challenge, I apply the algorithm proposed in Arkolakis et al. (2021), which exploits the single crossing differences in choice of the profit function and is well-suited for my setting where establishments are substitutes. The estimates report a 30 percent improvement in firm effective productivity, attributed to the strong correlation between ICT adoption and multi-unit production. The fixed costs of adopting ICT are estimated at US\$1.16–1.45 million, lower than the costs of setting up establishments at US\$2.37–\$4.57 million. Overall, the estimated model is able to replicate the bilateral firm expansion patterns in the data.

I use the estimated model to quantify efficiency gains from ICT development and shed light on policy designs. I begin with the 1995 Internet privatization that is used in estimation. I study this policy reform not only because it was one of the largest government ICT infrastructure projects in the US, but also the late 1990s was the last period when we saw significant aggregate productivity growth. I simulate this reform by lowering the cost of ICT 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, the Internet privatization increased efficiency by 1.3% on aggregate, accounting for around 10 percent of the overall manufacturing productivity growth from 1996 to 2000.[4] Notably, forty percent of this aggregate efficiency gain stems from firms' geographic expansion. Reduction in communication costs between headquarters and establishments accounts for another twenty-seven percent, while the improvement in firm-wide productivity accounts for the remainder. Local efficiency gains ranged from 0.9% to 1.5% for each location, and their distribution across locations is determined by the footprints of multi-unit firms and the entry and exit of their establishments. These results underscore the importance of taking into account multi-unit firms

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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 the privatization.

[4] The Bureau of Labor Statistics (BLS) reports a 9.4% increase in manufacturing total factor productivity between 1996 and 2000, corresponding to an average annual growth rate of 1.8 percent.

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. Particularly, 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 larger aggregate efficiency gain because of the cross-region spillovers through multi-unit production. Additionally, efficiency gains are widespread across locations. 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. For instance, the US Infrastructure Investment and Jobs Act includes programs promoting universal Internet penetration to reduce uneven Internet access. 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 improves our understanding of the gains from ICT improvements, a topic that has been extensively studied.[5] In closely related work, Bloom et al. (2014) use firm-level data and find a positive correlation between the firm span of control and the adoption of advanced ICT. Recent papers also document that ICT facilitates vertical fragmentation of production through phenomena such as outsourcing (e.g., Fort, 2017). Instead, this paper focuses on the impacts of ICT on firms' horizontal expansion across locations. I illustrate the mechanism in a model integrating firm ICT adoption with geographic expansion. I further use the estimated model to quantify the distribution of gains in improving ICT availability across locations in the United States.

This paper also complements the recent literature that studies differential effects of aggregate ICT cost reduction on local economic activities (e.g., Jiao and Tian, 2019; Rubinton, 2020; Eckert et al., 2020). To this end, I introduce multi-unit firms in a spatial equilibrium model. I show that the expansion of these firms and their location reoptimization are important in shaping the geographic distribution of economic activities.[6]

Firm expansion on the extensive margin has received increasing attention in the study of firm growth, and ICT has been a popular explanation for the extension of the firm's boundary (e.g., Cao et al., 2019; Hsieh and Rossi-Hansberg, 2019; Aghion et al., 2019). To the best of

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[5] 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; Van Reenen et al., 2007; Bloom et al., 2012; Baslandze, 2016; Lashkari et al., 2018). See Bresnahan (2010) and Goldfarb and Tucker (2019) for reviews of general purpose technology and recent development in digital economics.

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

my knowledge, however, there is no existing evidence on the causal relationship between firms' ICT adoption and geographic span of control. This paper fills this gap by conducting a series of quantitative analyses, including exploiting exogenous variation from a natural experiment and model simulation exercises.

The model builds on a growing literature studying the geographic organization of firms that produce at multiple locations (e.g., Ramondo and Rodríguez-Clare, 2013; Tintelnot, 2017; Hu and Shi, 2019; Hsieh and Rossi-Hansberg, 2019; Oberfield et al., 2020; Gumpert et al., 2022; Kleinman, 2022). In particular, the paper builds and extends on Tintelnot (2017) by incorporating the endogenous communication cost through ICT adoption. A key challenge for computing the firm's optimal set of production locations arises from the combinatorial choice problem; i.e., the cardinality of the choice set is on the order of 2^N, where N is the number of potential production locations. On the computation end, the paper contributes by applying the algorithm proposed in Arkolakis et al. (2021) to solve the firm location choice problem and by integrating this algorithm into the estimation procedure and counterfactual exercises.[7]

Finally, the estimation strategy using the Internet privatization is related to the literature on the effects of ICT infrastructure that exploits the interaction between time variation in the arrival of technology and geographic variation in the proximity to technology (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). Most of the previous literature focuses on the effects on local market outcomes such as employment and firm behavior.[8] Through the lens of the model, this paper shows that in addition to direct effects on local markets, ICT improvements have distributional effects across locations.

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

2 Data and Empirical Motivation

ICT has been a popular explanation for the extension of the firm's boundary. Most related research, however, relies on aggregate ICT data.[9] Leveraging US Census data, I provide micro-level relationship between ICT adoption, within-firm communication, and firms' geographic expansion.

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[7] Jia (2008) develops an algorithm based on the lattice theory to solve WalMart's entry decisions. Antras et al. (2017) integrate the algorithm in estimation to study importers' sourcing choices.

[8] Notable exceptions include Steinwender (2018), who studies the effect of telegraph development in the 18th century in the United Kingdom on trade and finds significant efficiency gains.

[9] For instance, using aggregate IT price changes and industry-level productivity trends, Aghion et al. (2019) propose IT as a driving force that widens the firm's boundary, such as the number of establishments a firm operates, and thus leads to productivity slowdowns, declines in the labor share, and rising industry concentration.

2.1 Data Sources

Longitudinal Business Database (LBD). I use the LBD from the US Census to construct firms' geographic footprints. It covers the universe of US establishments and provides consistent establishment and firm identifiers (LBDNUM and FIRMID, respectively), enabling me to link establishments to their parent firms and track the firms over time. The data also record the establishment ZIP code, county, state, employment, annual payroll, and industry codes constructed by Fort and Klimek (2018).[10]

I focus on firms' geographic expansion within industries, i.e., horizontal expansion. Recent literature has documented that the overall firm expansion is driven by their within-industry expansion across locations: while firms expand to more locations over time, they tend to specialize in fewer industries.[11] To measure within-industry expansion, I consider the establishments that a firm owns in each industry at the six-digit NAICS level. I do so by defining a firm by a FIRMID–industry pair, which is referred to as *firm* hereafter.[12] Nonetheless, I show that results regarding firms' expansion in all sectors are qualitatively consistent with my baseline results.

I use the number of establishments that a firm operates as the primary measure of its geographic span of control. Robustness checks consider alternative measures that represent broader geographic scopes, such as the number of counties, states, and census divisions and the number of establishments at a nondrivable distance.

Figure 1 shows that multi-unit firms, firms with more than one establishment in an industry, have more establishments over time.[13] It is worth noting that this trend does not solely reflect selection bias, as firms continuing to operate in an industry throughout the period have also been opening additional establishments. As these multi-unit firms account for a large share of US employment, understanding how ICT affects their geographic span of control has important aggregate implications.[14]

Computer Network Use Supplement (CNUS). I obtain information on ICT adoption from the CNUS, which is a supplement to the 1999 Annual Survey of Manufacturers (ASM). The key set of variables pertains to network adoption: the CNUS asks establishments whether they use

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[10] I focus on the contiguous US states. 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).

[11] Hsieh and Rossi-Hansberg (2019) documents that top firms in the US have reduced their sectoral coverage, reflecting increasing specialization. Ma (2022) shows that firms, particularly those engaging in R&D activities, have decreased their number of industries.

[12] The changes in the average number of establishments per FIRMID-industry equal the changes in the average number of establishments belonging to the same FIRMID, net of the changes in the average number of industries covered by the FIRMID. Appendix Section A.2 provides details of the decomposition.

[13] Panel A of Appendix Figure A.1 shows a similar trend for multi-unit firms in the manufacturing sector. Appendix Section A.3 examines how this trend aligns with the overall decline of the US manufacturing sector, as discussed in Fort et al. (2018).

[14] For instance, Bernard and Jensen (2007) document that multi-unit firms account for 78% of employment and 88% of output in the US manufacturing sector.

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 instance, an intranet—a private internal network that focuses on sharing information and smoothing communication among members inside the firm—reduces within-firm communication costs; an extranet—a private network that links the firm to its third parties such as customers and suppliers—expedites businesses with external parties. 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.[15] I aggregate the establishments' ICT adoption and communication to the corresponding firm level, assuming that a firm has adopted certain networks and communicates with internal and external parties if one of the firm's establishments does so. Nevertheless, my empirical results are robust to using alternative aggregation methods, such as taking averages across the firm's establishments. I also show robustness checks using establishments' ICT adoption and communication patterns.

Census of Auxiliary Establishments (AUX). Finally, I augment the LBD with the AUX to obtain headquarters employment, payroll, and locations for firms with stand-alone 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 for multi-unit firms. Appendix A.1 documents details of how I identify firm headquarters.

Summary Statistics. I link firms' geographic span of control from the LBD with their network adoption from the 1999 CNUS to conduct firm-level analysis. As the CNUS data do not include nonmanufacturing firms, my main analysis focuses on manufacturing firms and their establishments. Panel A of Table 1 presents summary statistics of the manufacturing firms in the LBD for the census years between 1977 and 2012, i.e., years ending in 7 or 2. There are 2,311,000 firm–year observations in the eight census years. Approximately 4% of these firms are multi-unit firms with more than one establishment.

Panel B presents summary statistics on firm ICT adoption, communication, and other firm characteristics of the CNUS sample. The variables regarding ICT delineate the state of technology adoption at the end of the twentieth century. The adoption rate of the basic Internet was high: 72.6% of firms were connected to the Internet in 1999, showing that the Internet was available to most businesses by then. However, the adoption rate was low for advanced technologies such as intranets, EDIs, and extranets, which relied on high-speed Internet and sophisticated infrastructure.[16] Around 36% of firms in the CNUS sample are multi-unit, with

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[15] The types of information include design specifications, product catalogs, demand projections, order statuses, production schedules, inventory data, and logistics and transportation information.

[16] Using establishment data from the CNUS, Appendix Table A.8 reports comparable adoption rates of dif-

2.3 establishments on average. While the Annual Survey of Manufacturers tends to cover larger firms, particularly multi-unit firms, these firms have substantially enlarged their geographic span of control. Rich data on their ICT adoption can help us study the role of ICT in these firms' geographic expansion.

2.2 Empirical Motivation

2.2.1 ICT Adoption and Geographic Expansion

I begin by using the LBD-CNUS linked data to provide firm-level correlation between the adoption of different networks and the firm's geographic expansion. These correlations suggest the relevance of various ICT channels, such as using an intranet for internal communication and an extranet for external communication, in the study of the firm's geographic expansion.

I measure the geographic expansion of a firm i around 1999 by its five-year growth rate in the number of establishments from 1997 to 2002 (i.e., $\Delta \widehat{\text{NumEstab}}_{i,97-02} = \log(\text{NumEstab}_{i,02}) - \log(\text{NumEstab}_{i,97})$) and estimate its correlation with the firm's network adoption in 1999 using the following regression:

$$\begin{aligned}\Delta \widehat{\text{NumEstab}}_{i,97-02} = \alpha &+ \beta_1 \text{Intranet}_{i,99} + \beta_2 \text{EDI}_{i,99} + \beta_3 \text{Extranet}_{i,99} \\ &+ \beta_4 \text{Internet}_{i,99} + \beta_5 \text{LAN}_{i,99} + \varepsilon_{i,97-02}, \end{aligned} \tag{1}$$

where the independent variables include indicators set to one if the firm installed an intranet, an EDI, an extranet, the Internet, or a LAN. To account for firms' initial conditions, I control for a vector of firm characteristics, including the logarithm of employment, firm age fixed effects, and state fixed effects at the beginning of the period. Since technology intensity may differ across industries, I include industry fixed effects at the four-digit NAICS level.

Panel A in Figure 2 plots the estimated coefficients for each type of network. The plot shows that firms' network adoption—in particular, intranet adoption—is associated with a higher growth rate in the firm's number of establishments. In contrast, the coefficient estimates for the other networks are statistically insignificant and economically small.[17] This comparison suggests that enhancing internal communication, which an intranet is designed to do, plays an important role in the geographic expansion of firms.[18]

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ferent technologies and communication patterns within the firm and with external parties. Forman et al. (2003) and Forman et al. (2012) use an alternative dataset, i.e., 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.

[17] 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 ($= 0.030/0.047 \times 100\%$).

[18] Bloom et al. (2014) use intranet adoption, obtained from the Harte-Hanks Ci Technology database, as a

The baseline results rely on the sample of firms and their establishments in the manufacturing sector for which network adoption data are available. Recent literature shows a shift of employment from the US manufacturing sector to other sectors. For instance, Fort et al. (2018) document that incumbent manufacturing firms have increased their nonmanufacturing employment by adding new establishments.[19] Therefore, I also consider the firm's overall expansion across sectors. Panel B shows that firms that adopted online networks are associated with a higher growth rate in the total number of establishments in all sectors. In addition to intranet, the other networks also display positive coefficients, although the magnitudes of their coefficients are smaller or insignificant.[20]

Several caveats are worth noting. First, these relationships are correlations and thus may not be casual. For instance, firms that plan to expand might have a higher incentive to adopt an intranet, leading to reverse causality. Second, as the network adoption data are available only for 1999, it is possible that firms adopted these networks after 1999. If so, my estimate may be considered a lower bound.

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 by $\text{WithinCommunication}_{i,99}$, an indicator set to one if any establishment of firm i shares information with other company units. Taking advantage of the rich data from the ASM, I am able to control for a wider set of firm characteristics, including the logarithm of employment, the logarithm of the capital-to-labor ratio, and the skill mix, measured by the ratio of nonproduction workers to production workers. I also include state and industry fixed effects.

Panel C 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. As this regression exploits cross-sectional variation, one may be concerned that a firm's intranet adoption is correlated with unobserved firm characteristics. To address this concern, I conduct two complementary analyses. First, I show that intranet adoption matters less for firms' external communication. If the result for within-firm communication is driven by unobservables that are

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proxy for the firm's internal communication costs.

[19] They show that electronic networks are positively correlated with firms' post-2000 growth in manufacturing employment and total employment in all sectors.

[20] Appendix Table A.11 shows additional results using the growth rates in firms' overall expansion in all sectors. Specifically, column (4) uses the growth rate in firms' total employment in all sectors as a dependent variable, which indicates that firms with advanced networks are associated with a higher growth rate. Another question is whether firms that adopted networks disproportionately expand in (non)manufacturing. As shown in column (5) of Table A.11, while most network adoptions are associated with larger growth rates in the firm's manufacturing employment share, the coefficients are statistically insignificant, reflecting firms' expansion in both the manufacturing and other sectors.

positively correlated with intranet adoption, the estimated coefficient of intranet adoption on external communication is likely to be upward biased as well. Panel D reports the results. The dependent variables corresponding to the circles and triangles are indicators set to one if a firm communicates with external customers and suppliers, respectively. Extranet adoption is most important for customer communication and Internet adoption 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.

Second, I leverage the establishment-level ICT adoption and communication patterns from the CNUS and exploit within-firm variation across establishments. Appendix Figure A.2 displays the results, where circles represent the regression coefficients using establishment-level data and triangles correspond to regressions that further include firm fixed effects. The findings align with the firm-level analysis and highlight the importance of intranets for within-firm communication, but relatively less for communication with external parties.[21]

Overall, the empirical evidence shows that ICT adoption is associated with higher likelihood of within-firm communication and geographic expansion. In the following section, I incorporate these findings with a structural model to provide a framework to quantify the efficiency gains from ICT improvements 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.

3.1 Model Setup

The economy consists of N locations, denoted by $\mathscr{N} = \{1, 2, \cdots, N\}$. In the following, I use "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 function. The settings on firms follow those in 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.

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[21] Appendix Table A.12 reports the regression coefficients.

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. Destination markets are denoted by k.

3.1.1 Demand

All varieties produced by firms are available to all markets. The representative consumer in each market k maximizes a CES utility aggregating all varieties with elasticity of substitution σ:[22]

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

where $y_{iok}(\omega)$ is the amount of variety ω shipped to market k by firm i, which is headquartered at o. Given product prices $p_{iok}(\omega)$ and the consumer's total expenditure on manufacturing goods E_k, we can solve the consumer's problem and obtain CES demand from market k for variety ω that produced by firm i :

$$y_{iok}(\omega) = E_k P_k^{\sigma-1} p_{iok}(\omega)^{-\sigma}. \tag{3}$$

P_k is the ideal price index of market k defined by:

$$P_k = \left(\sum_{o=1}^{N} \int_0^{m_o} \int_0^1 p_{iok}(\omega)^{1-\sigma} d\omega di \right)^{\frac{1}{1-\sigma}}, \tag{4}$$

which summarizes the prices charged to market k of all products in the economy.

3.1.2 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:

$$y_{ios}(\omega) = z_i \varepsilon_{is}(\omega) l_{ios}(\omega) / \gamma_{ios}. \tag{5}$$

In this expression, productivity includes two components: firm-specific productivity z_i, which affects all the firm's establishments and is iid across firms, and establishment-specific productivity $\varepsilon_{is}(\omega)$, 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 in location s, and the shape parameter

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[22] The elasticity of substitution is assumed to be identical among varieties within and across firms. Antràs et al. (2022) relax this assumption and allow for different elasticities within and across firms.

θ determines the dispersion of establishment productivity draws. $l_{ios}(\omega)$ is the local labor input.

Communication costs and ICT. γ_{ios} is an iceberg-type communication cost. Motivated by the empirical evidence that firms with advanced ICT—such as intranets—have lower barriers of communicating internally, I assume γ_{ios} is lower if the firm adopts better ICT.

Let φ_i denote firm i's ICT level. As I only observe the binary network adoption, I categorize φ_i into two levels—low and high, i.e., $\varphi_i \in \{\underline{\varphi}, \overline{\varphi}\}$. In the following, I work with simple yet flexible communication technology, in which I decompose γ_{ios} into two terms:

$$\gamma_{ios} = \gamma_{os}(\varphi_i) = \underbrace{h(\varphi_i)}_{\text{firm-wide}} \quad \underbrace{d_{os}(\varphi_i)}_{\text{HQ-establishment}} \tag{6}$$

The first term reflects the firm-wide communication cost and can be viewed as a firm productivity shifter. The second term is specific to the firm headquarters–establishment location pair, capturing the communication costs due to remote production. Firms with a high ICT level face lower communication costs with nonheadquarters establishments, i.e., $d_{os}(\underline{\varphi}) \geq d_{os}(\overline{\varphi}) \geq 1, s \neq o$. Local production does not incur this type of costs, i.e., $d_{oo}(\underline{\varphi}) = d_{oo}(\overline{\varphi}) = 1$.

Variable costs. The unit cost of firm i producing a variety ω at an establishment in location s and shipping it to market k is:

$$c_{iosk}(\omega) = \underbrace{(z_i/h(\varphi_i))^{-1}}_{\substack{\text{firm effective}\\ \text{productivity}}} \ \underbrace{(\varepsilon_{is}(\omega))^{-1}}_{\substack{\text{local}\\ \text{productivity}}} \ \underbrace{w_s}_{\substack{\text{input}\\ \text{cost}}} \ \underbrace{\tau_{sk}}_{\substack{\text{shipping}\\ \text{cost}}} \ \underbrace{d_{os}(\varphi_i)}_{\substack{\text{communication}\\ \text{cost}}} \ , \tag{7}$$

which summarizes the firms' effective productivity, local productivity, local input costs, shipping costs to the destination market, and communication costs from headquarters to establishments.

Adopting better ICT reduces variable production costs through two channels. First, it increases firm-wide productivity through $h(\varphi_i)$. Second, ICT reduces the headquarters–establishment communication cost $d_{os}(\varphi_i)$. Identifying the magnitude of these two channels is crucial to quantify the benefits of ICT adoption on overall production efficiency.

Fixed costs. Firms face a fixed cost, denoted by f^X_{ios}, when they set up additional establishments besides their headquarters, with this cost depending on the locations of the establishment and headquarters. Similarly, firms pay a fixed cost, denoted by f^{ICT}_{io}, if they choose to adopt a high ICT level, and this cost varies across headquarters locations. Both fixed costs are firm-specific to reflect the varying expansion and ICT adoption decisions for firms with similar characteristics in 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.

3.1.3 The Firm's Optimization Problem

Firms decide whether to adopt a high ICT level, choose optimal sets of production locations, hire labor, produce a continuum of varieties, and serve markets. I first derive the firm's optimal profit given establishment locations and ICT status. I then solve for the optimal locations and ICT adoption. Appendix B provides more details.

Production Given a Set of Establishment Locations and States of ICT

To ease notation, I now index firms headquartered at o by their productivity z. Let the firm's set of locations S and its ICT level φ be fixed. For each market k and each variety $\omega \in [0,1]$, the firm chooses one of its establishments $s \in S$ that has the lowest unit cost $c_{osk}(\omega, \varphi, z)$, defined in Equation (7), to serve the market. Thanks to the properties of the Fréchet distribution for establishment productivity ε, the share of sales to a market k from establishment $s \in S$ is

$$\zeta_{ok\leftarrow s}(S,\varphi,z) \equiv \frac{\text{sales}_{ok\leftarrow s}(S,\varphi,z)}{\text{sales}_{ok}(S,\varphi,z)} = \frac{(T_s/w_s)^{\theta}(\tau_{sk}d_{os}(\varphi))^{-\theta}}{\Phi_{ok}(S,\varphi)}. \tag{8}$$

The denominator is the firm's "production potential" for serving market k, defined by:

$$\Phi_{ok}(S,\varphi) = \sum_{s\in S}(T_s/w_s)^{\theta}(\tau_{sk}d_{os}(\varphi))^{-\theta}, \tag{9}$$

which 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 communication costs to the headquarters ($d_{os}(\varphi)$) that are endogenous to the firm's ICT level.

Given the CES demand, we can derive the firm's profit from market k:

$$\pi_{ok}(S,\varphi,z) = \frac{\sigma^{-\sigma}}{(\sigma-1)^{1-\sigma}}\tilde{\Gamma}E_k P_k^{\sigma-1}\left(\frac{z}{h(\varphi)}\right)^{\sigma-1}\Phi_{ok}(S,\varphi)^{\frac{\sigma-1}{\theta}}, \tag{10}$$

where σ is the elasticity of substitution, $\tilde{\Gamma} = \Gamma\left(\frac{\theta-\sigma+1}{\theta}\right)$ is a constant, E_k and P_k are the consumer's total spending on manufacturing goods and the ideal price index in location k, respectively.[23]

ICT adoption increases profits through enhancing the firm's effective productivity, $z/h(\varphi)$, and improving its production potential, $\Phi_{ok}(S,\varphi)$, by reducing internal communication costs $d_{os}(\varphi)$. The latter allows for rich interaction between ICT 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.

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[23] I assume $\theta > \sigma - 1$ so that $\tilde{\Gamma}$ is properly defined. Appendix B.2 provides more details on the derivation.

Optimal Set of Establishment Locations and ICT Adoption

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

$$\pi_o(z) = \max_{\varphi \in \{\underline{\varphi}, \overline{\varphi}\}} \pi_o(\varphi, z) - \mathbb{1}[\varphi = \overline{\varphi}] f_o^{ICT}, \tag{11}$$

where the profit conditional on the ICT level, $\pi_o(\varphi, z)$, comes from the following optimization:

$$\pi_o(\varphi, z) = \max_{S \in \mathscr{S}} \sum_{k=1}^{N} \pi_{ok}(S, \varphi, z) - \sum_{s=1}^{N} \mathbb{1}[s \in S] f_{os}^X, \tag{12}$$

where $\pi_{ok}(S, \varphi, z)$ is defined above in Equation (10). It is worthwhile noting that the firm's location choice problem in (12) is a combinatorial discrete choice problem. The possible location combinations grow exponentially, making it challenging to solve. To address this, I use the algorithm from Arkolakis et al. (2021). Appendix C.4 shows that a sufficient condition, the single crossing differences condition, applies to my setting and outlines the computation algorithm.

3.1.4 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.[24]

Definition: Equilibrium is a vector of prices $\boldsymbol{P}$ consistent with firm optimization in Equation (10) to (12), and clears the product market for each location $k = 1, \cdots, N$:

$$\eta G_k = P_k Y_k, \text{ where } P_k = \Big(\sum_{o=1}^{N} \int_Z p_{ok}(z)^{1-\sigma} d\mu_o(z) \Big)^{\frac{1}{1-\sigma}}, Y_k = \Big(\sum_{o=1}^{N} \int_Z y_{ok}(z)^{\frac{\sigma-1}{\sigma}} d\mu_o(z) \Big)^{\frac{\sigma}{\sigma-1}} \tag{13}$$

where μ_o denotes the exogenous measure of firms headquartered in location o and Z the support of firm productivity. $p_{ok}(z)$ and $y_{ok}(z)$ are the firm-level price index and sales, respectively, to

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[24] I assume that labor supply is perfectly elastic, and wages are treated as exogenous. Nevertheless, key mechanisms are still operative in endogenous labor markets regarding the equilibrium effects on firm expansion decisions. Consider the extreme case in which labor supply is perfectly inelastic. With endogenous labor markets, as the fixed cost decreases, labor demand increases, thus driving up wages. The production potential term $\Pi_{ok}(S, \varphi)$, which is a function of the inverse of wages, decreases. Price indexes decrease, and expenditure increases, with the two offsetting each other. The equilibrium effect, again, works as a countervailing force that reduces the appeal of geographic expansion.

market k from a firm headquartered in location o and with productivity z.[25]

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

3.2 Model Characterization

3.2.1 ICT Adoption and Firm Geography

I illustrate the impacts of ICT adoption on firm geography at both extensive and intensive margins using a simplified example with three locations: a firm's headquarters location (HQ), a nearby location with relatively low local productivity and a low fixed cost of setting up establishments (L), and a faraway location that is more productive but also incurs a higher fixed cost (H). The firm evaluates the benefits and costs of each of the four combinations of establishment locations: $\{HQ\}$, $\{HQ, H\}$, $\{HQ, L\}$, and $\{HQ, H, L\}$. For example, adding an establishment at L is only worthwhile if the additional gross profit exceeds the fixed cost of setting up the establishment there.

Extensive Margin. I first demonstrate how the model captures the main empirical motivation: on the extensive margin, ICT adoption expands firms' geographic span of control by lowering internal communication costs. Panel A in Figure 3 displays the policy function of the number of establishments against firm fundamental productivity z, along with the set of locations. The dotted line corresponds to a low level of ICT; the solid line corresponds to a high level of ICT. 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, while more productive firms expand to H, even the number of establishments remain the same. By enhancing firm-wide productivity $h(\varphi)$ and reducing headquarters–establishment communication costs $d_{os}(\varphi)$, ICT 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 expanding are larger for firms that adopt better ICT, and the benefits of adopting ICT is larger for firms with a larger set of locations. When considering both decisions together, less productive firms maintain low ICT and local production, while more productive firms adopt better ICT and further expand their geographic footprints. The complementarity is discussed in more details in Appendix B.4.

Intensive Margin. On the intensive margin, ICT adoption affects within-firm sales distribution across establishments by changing $d_{os}(\varphi)$, even if the firm's location choice remains the same. Suppose $d_{os}(\varphi)$ is log-linear in the distance between o and s, $d_{os}(\varphi) = e^{\beta^d(\varphi)\log \text{Miles}_{os}}$ for $s \neq o$,

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[25] 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 $y_{ok}(z) = E_k P_k^{\sigma-1} p_{ok}(z)^{1-\sigma}$.

where the elasticity $\beta^d(\varphi)$ depends on the firm's ICT level. Firms with better ICT face a smaller elasticity, i.e., $\beta^d(\overline{\varphi}) \leq \beta^d(\underline{\varphi})$, meaning that the communication cost increases slower in distance for those firms.

Panel B in Figure 3 shows the impact of ICT on establishment sales for firms operating in $\{HQ, L, H\}$ even with low ICT. Relative to the headquarters sales, the establishment sales decreases as it becomes further away from the headquarters. However, the rate of decrease is smaller if firms adopt high ICT, driven by a lower internal communication elasticity $\beta^d(\varphi)$. ICT adoption results in firms allocating more sales to nonheadquarters and distant establishments.[26].

Indeed, we can derive the within-firm sales share of an establishment in s and normalize it by the sales at the firm's headquarters o:

$$\log \tilde{\zeta}_{os}(S,\varphi) = -\theta\beta^d(\varphi)\log \text{Miles}_{os} + \log\left(\frac{\sum_k \omega_{ok}(S,\varphi)\tau_{sk}^{-\theta}}{\sum_k \omega_{ok}(S,\varphi)\tau_{ok}^{-\theta}}\right) + \theta \log\left(\frac{T_s}{T_o}\right) - \theta\log\left(\frac{w_s}{w_o}\right) \quad (14)$$

The first term on the right-hand side indicates the communication cost between o and s, depending on ICT level φ. The second term represents the normalized establishment's market access, i.e., the weighted average shipping costs from the establishment to all markets k.[27] The last two terms represent the normalized local productivity and input cost at s.

In the above equation, firm-specific components—productivity z and firm-wide communication costs $h(\varphi)$—are canceled out, which allows us to separate the two ICT channels via $h(\varphi)$ and $d_{os}(\varphi)$. In Section 4, I use this insight to provide an estimation framework that exploits the within-firm labor allocation to quantify the effect of ICT adoption on communication costs between headquarters and establishments $d_{os}(\varphi)$.

3.2.2 Equilibrium Effects of an ICT Cost Reduction

Now I analyze how a decrease in ICT costs, resulting from technology and infrastructure improvements, affects a firm's location choices and local efficiency.

Effects on Firm Location Choices. Following a reduction in the fixed cost of adopting ICT, on the one hand, firms are more likely to adopt ICT, which leads to expansion due to complementarity between the two decisions. On the other hand, increased efficiency and expansion result in a more competitive market, reflected in lower price indices $\boldsymbol{P}$, which can lead to firm contraction.

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[26] Appendix B.3 proves in a three-location example that ICT adoption increases the sales share of nonheadquarters and distant establishments.

[27] Particularly, the weight for a market k is $\omega_{ok}(S,\varphi) = \frac{E_k P_k^{\sigma-1}\Phi_{ok}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}}{\sum_{k'} E_{k'} P_{k'}^{\sigma-1}\Phi_{ok'}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}}$, which depends on the firm's ICT and geographic footprint via its production potential $\Phi_{ok}(S,\varphi)$. $\omega_{ok}(S,\varphi)$ gives more weight to the market k to which the firm has smaller production potential, in comparison to the weight that considers only market demand, defined by $\tilde{\omega}_k = E_k P_k / \sum_{k'} E_{k'} P_{k'}$. For instance, a firm that is headquartered in the Pacific census division and has an additional establishment in New England places smaller weights on market demand from the Pacific, where the firm has relatively high production potential.

Ultimately, the net changes in the firm's geographic span of control in equilibrium depend on the relative strength of these two forces. Appendix Figure A.5 decomposes the equilibrium effects into these two forces in the same three-location example as in the previous section. Appendix B.5 provides more details.

Efficiency Gains. Absent multi-unit production, local efficiency is determined by two factors: (i) the local production of firms headquartered in the location (i.e., local firms), and (ii) the traditional trade channel of firms headquartered in other locations (i.e., outside firms). However, with the option of multi-unit production, local efficiency is also impacted by two additional factors: (iii) the local production by outside firms, and (iv) the third-location trade by firms' nonheadquarters production, which is referred to as the exporting platform in Tintelnot (2017).[28]

Multi-unit firms play a crucial role in the equilibrium distribution of efficiency gains across locations. First, the adoption of better ICT leads to increased productivity of existing establishments of multi-unit firms in different locations, thus influencing efficiency elsewhere. Second, when firms reoptimize their location choices, the entry and exit of their establishments also affect efficiency in other locations. To clarify these channels, Appendix Section B.6 provides a decomposition of local efficiency that distinguishes the contributions from different types of firms, highlighting the spread of efficiency gains across locations through the additional channels by multi-unit production.

Finally, to quantify efficiency gains, it is crucial to estimate the effects of ICT on production efficiency. In the next section, I turn to the estimation.

4 Estimation

Key parameters concern the extent to which ICT adoption affects the firm-wide productivity $h(\varphi)$ and the headquarters–establishment communication cost $d_{os}(\varphi)$. 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' ICT adoption. Sections 4.1 describes the parameterization and estimation strategy. Section 4.2–4.4 discuss the three steps of estimation.

4.1 Parameterization

Location in the model. I define the location at the census division level. This operationalization captures meaningful firm expansion patterns. When multi-unit firms add establishments,

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[28] As the mass of firms is exogenous and there is no fixed cost of exporting, the set of varieties is exogenous and does not vary with the mass of establishments, which is endogenously determined in equilibrium.

a majority of the new establishments are located in census divisions different from those where the firms are headquartered.

Firm productivity distribution. I assume that firm productivity follows a log-normal distribution with mean μ^z and dispersion σ^z.

Trade costs. Trade costs are log-linear in distance, measured in miles, between the production establishment (s) and the destination market (k) with elasticity β^τ: $\tau_{sk} = e^{\beta^\tau \log \text{Miles}_{sk}}$.

Communication costs. First, I assume that headquarters–establishment communication costs $d_{os}(\varphi)$ are log-linear in distance, measured in miles, between the firm's headquarters (o) and establishment (s): $d_{os}(\varphi) = e^{\beta^d(\varphi) \log \text{Miles}_{os}}$, for $s \neq o$; communication costs within the headquarters are normalized to 1, i.e., $d_{oo}(\overline{\varphi}) = d_{oo}(\underline{\varphi}) = 1$. Importantly, I allow the communication elasticity $\beta^d(\varphi)$ to vary between firms with low and high ICT: $\beta^d(\varphi) = \beta^d_1 + \beta^d_2 \times \mathbb{1}[\varphi = \overline{\varphi}]$. Guided by the empirical result that having an intranet lowers a firm's internal communication costs, I use firms' intranet adoption as a proxy for the ICT level, so $d_{os}(\varphi) = e^{\beta^d_1 \log \text{Miles}_{os} + \beta^d_2 \log \text{Miles}_{os} \times \text{Intranet}}$.[29]

Second, the firm-wide communication costs $h(\varphi)$ take two values, since ICT is discretized into two levels. The one associated with low ICT is denoted by $\underline{h}$, and the one with high ICT by $\overline{h}$.

Fixed costs. I parameterize the fixed costs of adopting ICT to be log-normally distributed, with mean μ_o^{ICT} and dispersion σ^{ICT}. As I will turn to in more details, I add to the model that locations closer to the Internet backbone nodes face lower costs of adopting ICT. 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: $\mu_o^{ICT} = \beta_1^{ICT} + \beta_2^{ICT} \log(\text{HQ}\widetilde{\text{DistToNode}}_o)$.

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. I set the elasticity of substitution across varieties $\sigma = 4$, the center value in the range of estimates used in the international trade literature (see Head and Mayer, 2014). 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).[30] 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 US Census of Manufacturers to estimate the distribution

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[29] 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.

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

of firm productivity.[31] 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 the cost with a higher ICT $\overline{h} = 1$. Panel A of Table 2 presents the assigned parameters.

Estimated parameters. I estimate the rest 18 parameters in three steps. In the first step, I estimate the headquarters–establishment communication costs for low and high ICT (β_1^d, β_2^d). In the second step, I back out the scale parameters of the Fréchet distribution for establishment productivity in each location ($T_s, s = 1, \cdots, 9$). In the last step, I use the method of simulated moments (MSM) to jointly estimate the firm-wide communication cost associated with low ICT ($\underline{h}$), distribution of fixed costs of setting up establishments ($\beta_1^X, \beta_2^X, \sigma^X$), and distribution of fixed costs of adopting ICT ($\beta_1^{ICT}, \beta_2^{ICT}, \sigma^{ICT}$). Panel B of Table 2 summarizes the estimated parameters.

4.2 Estimating Headquarters–Establishment Communication Costs

I first estimate how the elasticity of headquarters–establishment communication costs with respect to distance varies by firm's ICT level, which is one of the two channels through which ICT affects production efficiency.

4.2.1 Estimating Equation

Equation (14) relates the within-firm establishment sales shares to communication costs from the establishment at s to headquarters at o. It says that, given the firm's set of locations and establishment location characteristics such as market access, the establishment's sales share relative to the headquarters is determined by the headquarters–establishment communication costs, $\beta^d(\varphi) \log \text{Miles}_{os} = \beta_1^d \log \text{Miles}_{os} + \beta_2^d \log \text{Miles}_{os} \times \text{Intranet}$, as I use the firm's intranet adoption as a proxy for ICT (φ). Thus, I exploit within-firm variation in establishment shares and compare the relationship between these shares and their distance to headquarters for firms with low and high ICT levels.

There are a few details worth noting to take Equation (14) to the data. First, sales data were unavailable in the LBD until recently and are at the firm level. Fortunately, the LBD provides detailed employment data at the establishment level. Therefore, I instead use the within-firm

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[31] Guner et al. (2008) estimate the distribution of firm productivity, defined as managerial ability, by matching the size distributions of US 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 setting, I apply a factor of $1/(\sigma - 1)$ to their estimated mean and dispersion to be consistent.

employment shares to perform the estimation. Appendix C.1 shows that the employment share is analogous to the sales share.

Second, I approximate the weighted average market access by $(\phi+\phi_{oS\varphi})\log\left(\sum_k \frac{N_k\bar{y}_k}{\sum_{k'}N_{k'}\bar{y}_{k'}}\tau_{sk'}^{-\theta}\right) \equiv (\phi+\phi_{oS\varphi})\log\overline{MA}_s$, where N_k is the population of location k and $\bar{y}_k$ is the location's per capita income. Consistent with the model, the slope $\phi_{oS\varphi}$ captures differential impacts of market access by firm headquarters location, other establishment locations, and firm ICT levels.[32]

Denote the firm by i and its intranet adoption by Intranet_i. Together with the parameterization, we can derive the following estimating equation from Equation (14):

$$\log\tilde{\zeta}_{ioS\varphi,s} = -\theta\beta_1^d \log \text{Miles}_{os} - \theta\beta_2^d \log \text{Miles}_{os} \times \text{Intranet}_i + \phi_{oS\varphi}\log\overline{\text{MA}}_s + \xi_{oS\varphi} + \xi_s + \varepsilon_{ioS\varphi,s}. \tag{15}$$

The employment share of an establishment changes in the distance to the firm's headquarters, all else equal, and this elasticity varies with the firm's intranet adoption. $\xi_{oS\varphi}$ and ξ_s are headquarters–set–ICT and establishment location fixed effects, respectively.[33] $\varepsilon_{ioS\varphi,s}$ is a random disturbance. I also include industry fixed effects to control for industry heterogeneity. Note that factors impacting firm-wide components, such as firm productivity, are canceled out as we normalized establishment employment shares by the firm headquarters share. This allows me to isolate the impact of ICT on communication costs between headquarters and establishments.

In Equation (15), if indeed establishments become smaller as they are farther away from the headquarters, the coefficient on $\log \text{Miles}_{os}$ would be negative. The coefficient on the interaction term is crucial. Particularly, a positive coefficient would suggest that establishments belonging to firms with intranets experience a slower decline in size, as the model implies.

In sum, this regression not only tests the model, but also estimates the second channel through which ICT improves internal communication.

4.2.2 Instrumental Variable from the Internet Privatization

One concern is that firms selecting into ICT adoption might be systematically different. For instance, firms with large establishments in faraway locations may be more likely to adopt better ICT, leading to an upward bias of the impact of ICT. To address this concern, I supplement the OLS regression with an instrumental variable approach that exploits natural experimental

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[32] Given the firm's headquarters location, set of locations, and ICT level (i.e., intranet adoption status), the correlation between the model-derived market access and the linear approximation is 0.97, on average. The high correlation indicates that linear functions of market demand–weighted market access approximate the market access term reasonably well.

[33] 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. The coefficient on $\log\overline{MA}_s$ in the first-step regression, i.e., $\phi_{oS\varphi}$ is identified by the differential relationship between establishment employment shares and market access across firms with different headquarters–set–ICT statuses.

variation in ICT cost reduction from a milestone in early US Internet history—the Internet privatization. This event also allows me to test an important model implication on firms' geographic expansion following ICT cost reduction.

I summarize this event below. Appendix C.2 provides more details.

Internet privatization. The first high-speed Internet backbone in the US, NSFNET, was launched in 1986 and operated by the government through the NSF. By the early 1990s, it connected sixteen node sites across the US as shown in Figure 4, reflecting historical factors related to proximity to military bases and university locations.[34] Each node was connected to regional networks.

NSFNET was originally for the use of the research and higher education community, so its commercial use was restricted. 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. Privatization of the Internet was finalized on April 30, 1995. Following privatization, the Internet gold rush started.[35] Appendix Figure A.3 shows a surge in the number of Internet service providers advertised in a national magazine since then.[36]

I use the privatization of NSFNET as a natural experiment. To measure the firm's exposure to this event, 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 one major cost for Internet service providers, the costs of Internet access for businesses were lower if they were in locations with better infrastructure.[37] In the following empirical analysis, I measure the distance at the zip code level, while the structural estimation are consistently conducted using measures at the census division level.

First-stage evidence. Although panel data on firms' ICT adoption are not available, I use firms' intranet adoption in the 1999 CNUS data to provide first-stage evidence. Since intranets

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

[35] The conversation concerning the privatization of the Internet started from the early 1990s, and commercial businesses were allowed to connect to the Internet around 1992. Nevertheless, the final privatization of the Internet in 1995 served as a catalyst of the Internet gold rush. See Appendix Section C.2 for more details on the development and privatization of NSFNET.

[36] This figures 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.

[37] McKnight and Bailey (1998) documented 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—a world leading enterprise resource planning (ERP) provider—to measure firms' probability of adopting ERP software. Forman et al. (2012) use county-level variation in the number of nodes for ARPANET—the predecessor of NSFNET—as an instrument for local advanced IT investment by businesses.

were commercialized after privatization, their adoption rate in 1999 reflects the change in the technology adoption. I sort firms according to their distance to the nearest NSFNET node (in hundreds of miles), denoted as HQDistToNode, and calculate the fraction of firms that adopted an intranet within each distance quintile. To ensure locations and firms are comparable along the distance, I control for county characteristics and include industry and state fixed effects. Figure 5 shows that firms located closer to nodes were more likely to have adopted an intranet in 1999 after the Internet privatization, indicating 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 on the firms' geographic span of control to test a key model implication on the extensive margin: ICT cost reduction 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 intranet.

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

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

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 results are robust to other measures that capture a broader geographic scope such as the number of states, census divisions, and so forth. 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 faraway from the nodes, and how their geographic span of control is affected by privatization. I include industry–year and state–year fixed effects to control for differential trends across industries and states, where industry is at the 4-digit NAICS level. One may be concerned that firm growth may be correlated with local conditions. I show that results are robust to including county–year-specific characteristics, such as the logarithm of the 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.[38]

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.9 reports the summary statistics of the balanced sample.

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

Identification assumption is that the Internet privatization did not coincide with other location-by-year shocks. To validate this assumption, I show graphical evidence that firms display similar trends in their geographic scope before privatization, regardless of proximity to the backbone nodes. Figure 6 plots the estimated coefficients β_t and 95 percent 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 post 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.[39]

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:

$$Y_{it} = \alpha_i + \beta \text{HQDistToNode}_i \times \text{Post}_t + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it}, \tag{17}$$

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

Column (1) of Panel A estimate 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) shows 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 generalized propensity scores, conditional on firm and county characteristics before the privatization, and applying inverse propensity score method (IPW) to ensure firms and locations located closer to NSFNET nodes are comparable from those far away.[40] 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 a 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) and (5) consider the number of establishments outside the headquarters state

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[39] The long-lasting effects might suggest constant arrival of new technologies or initial competitive advantages for firms expanding at an early stage.

[40] Appendix Figure A.4 shows that after the propensity score reweighting, firm and county characteristics are balanced along the distance. Appendix C.3.1 provides more details on how I construct the generalized propensity scores of treatment (see Robins et al., 2000; Hirano and Imbens, 2004; Abadie, 2005).

and at a nondrivable distance (i.e., over 250 miles away) from the headquarters, respectively.

I also test whether firms close to nodes tend to open new establishments close to the nodes as well. I do so by replacing the dependent variable with the average distance from the firm's *new establishments* to the nearest NSFNET nodes. As shown in column (1) of Panel C, the estimated coefficient is positive and statistically significant, indicating 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 ICT. Columns (2)–(5) suggest that firms closer to nodes also tend to locate new establishments in counties with higher household incomes and younger populations, but similar local population or the share of bachelor's degrees.

Appendix Table A.13 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.[41] Appendix Table A.14 presents additional results regarding firms' employment.

In sum, the reduced-form evidence shows that firms expand geographically following a large reduction in ICT costs, which validates a key model implication on the extensive margin.

Instrumental Variable. 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 (17) and restrict to years up to 1999 to minimize the scope of measurement errors resulting from the construction of my time-varying intranet variable.[42]

The first-stage regression takes the same form as Equation (17) but replaces the dependent variable with the firm's intranet adoption:

$$\text{Intranet}_{it} = \alpha_i + \beta \text{HQDistToNode}_i \times \text{Post}_t + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it}. \tag{18}$$

Column (1) of Table 4 shows that firms located 100 miles closer to a node are associated with 3.5 percentage points higher probability of adopting an intranet, more than doubling the

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[41] Column (3) of Appendix Table A.13 excludes firms headquartered within 250 miles to the nodes that are university towns, which include Princeton, Champaign, Ithaca, Palo Alto, Ann Arbor, College Park, and Cambridge.

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

likelihood on average ($= 0.035 \times 130/0.036$). 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. Column (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 higher 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 that the Internet privatization, particularly HQDistToNode_{it}, affect firms ICT adoption.

Finally, I use the predicted probability of intranet adoption of a firm i in 1999 from Equation (18), i.e., $\widehat{\text{Intranet}}_{i,99}$, as an instrument for Intranet_i in the structural estimating equation (15), 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 (15) using the firms and their establishments in the LBD–CNUS matched sample. I further restrict to firms with establishments in at least two census divisions besides their headquarters, as identification requires variation across nonheadquarters establishments. Table 5 shows the results. Columns (1)–(2) abstract away from ICT adoption, serving as a first pass for the relationship between establishment employment shares and distances to headquarters. Column (1) covers observations throughout 1987–2007. The estimated coefficient on Log(Miles) is -0.172, indicating that a 10% reduction in the distance leads to a 1.7% increase 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) 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 $\beta^d_{\text{High ICT}} = 0.072 = ((0.652 - 0.394)/3.6)$, 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.[43] Notably, the elasticity of communication costs is

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[43] The instrument has a reasonably well predictive power with a first-stage F-stat of 15.27. The estimated coefficients shows $\beta^d_{\text{Low ICT}} = 0.334$ 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 take into account both the first- and second-stage regressions.

generally smaller than that of trade costs with respect to distance, suggesting that local shocks, such as local productivity shocks, can diffuse to other locations faster through the multi-unit production channel within the firm than through the trade channel.[44]

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.

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

4.3 Estimating Local Productivity

In Equation (15), which draws on the model structure, we can write the location fixed effect as:

$$\xi_s = \theta \log T_s - (\theta + 1) \log w_s + \phi \log \overline{MA}_s, \tag{19}$$

which captures the establishment location's local productivity, wage costs, and average market access. The first-step regression in column (1) of Table 5 delivers a vector of fixed effect estimates for each census division s and year t, i.e., $\hat{\xi}_{st}$. In the second step, I decompose these estimates to back out the local productivity, i.e., the scale parameters of the location-specific Fréchet distributions T_s.

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 for census division s and year t.[45] Columns (1) and (2) in Table A.16 report the raw and purified fixed effects, respectively, for each census division in 1999, normalized by the estimate for the New England census division.[46]

Then, to estimate the coefficient ϕ, I follow the convention by approximating the local state of technology (T_{st}) by the local R&D stock and estimate the following regression:

$$\tilde{\xi}_{st} = b_0 + b_{RD} \log \text{R\&D}_{st} + \phi \log \overline{MA}_{st} + \gamma_t + \delta_s + u_{st}, \tag{20}$$

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[44] Giroud and Mueller (2019) show that local housing price shocks spill over to other regions through firms' internal network, i.e., establishments with the same parent firm.

[45] The education-adjusted wage is calculated by $w_{st}^{\text{adj}} = w_{st} \exp(\mu H_{st})$, where H_{st} is the average years of schooling in census division s and year t and μ is the return to schooling, which is set to 0.06 following Bils and Klenow (2000).

[46] The purified fixed effects depend on the value of θ, which is calibrated to 3.6 here, but the implied location's state of technology is highly correlated when θ varies.

where $\tilde{\xi}_{st}$ is the purified location fixed effects, $\log \text{R\&D}_{st}$ and $\log \overline{MA}_{st}$ are the logarithm of the local R&D stock and local market access, respectively.[47] γ_t is year fixed effect. δ_s is census division fixed effect.

Table 6 shows estimated coefficients. Columns (1) and (2) control for R&D stock and market access, respectively, while 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), the elasticity with respect to market access (i.e., $\hat{\phi}$) is estimated at 0.743. Given this estimate, I can construct T_{st} by $\log(T_{st}) = (\tilde{\xi}_{st} - \hat{\phi} \log \overline{MA}_{st})/\theta$, reported in column (3) of Table A.16.[48] Local productivity differs from the purified fixed effect due to market access. For example, compared to the New England, the Middle Atlantic has a higher local fixed effect but a lower state of technology, indicating that it is mostly better market access that drives up its appeal.

4.4 Estimating Firm-Wide Communication Costs and Fixed Costs of ICT Adoption and Geographic Expansion

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

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

$$g(\psi) = [m - \hat{m}(\psi)]' W [m - \hat{m}(\psi)], \tag{21}$$

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. Each firm draws a productivity z, a fixed cost of ICT adoption f_o^{ICT}, and a vector of fixed costs of setting up establishment 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. To expedite

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[47] I construct the local R&D stock by the perpetual inventory method using industrial R&D expenditure. State-level R&D expenditure data are from the Survey of Industrial Research and Development, available from the NSF website. 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. For instance, $\text{R\&D}_{1990}^{\text{exp}} = (\text{R\&D}_{1989}^{\text{exp}} + \text{R\&D}_{1991}^{\text{exp}})/2$. 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 I assume the depreciation rate to be 0.15.

[48] The state of technology is also normalized by that of the New England census division.

computation, I adopt the algorithm proposed by Arkolakis et al. (2021).[49]

Moments and identification. Table 7 summarizes the three sets of targeted moments I constructed from the LBD–CNUS matched sample.

(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 costs of setting up establishments (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 were 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., $\%\text{Firms}_{os}$) and the log miles between the two census divisions identifies the role of distance in the fixed costs (β_2^X).

(ii) The second set of moments inform us about the fixed costs of ICT adoption. Moments include the overall share of firms that adopt an intranet, the share of adopting firms with employment below the median, and the correlation between a firm's ICT adoption and the logarithm of the average distance to the nearest NSFNET node from the firm's headquarters.[50] Similarly, these moments identifies the mean and dispersion of the fixed costs of ICT adoption and the role of distance to nodes in these fixed costs.

(iii) The last moment concerns an important complementarity the model captures—the correlation between a firm's ICT adoption and its multi-unit status—and helps identify the firm-wide communication cost for low ICT ($\underline{h}$). The higher the correlation, the larger the difference in communication costs for low- and high-ICT firms.

Estimation results. The last panel in Table 2 reports the third-step estimation results.[51] $\underline{h}$ is estimated to be 1.335. As the cost for high ICT level is normalized to 1, this implies that ICT adoption enhances firm productivity by approximately 28.9%$(= \log 1.335 - \log 1)$.

The fixed costs of setting up establishments (f_{os}^X) increase with distance, with an elasticity of 0.073. Column (1) in Table A.17 displays the monetary value of the conditional average fixed

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[49] Appendix C.4 demonstrates that my settings meet the single crossing differences condition, which is a sufficient condition for this algorithm.

[50] 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.

[51] Figure A.6 plots the loss function against each parameter with the other parameters held at their estimated values, confirming that the estimates minimize the criterion function.

costs paid by firms expanding to each census division.[52] The costs range from \$2.37 million in the West North Central to \$4.57 million in the South Atlantic. Through the lens of the model, these costs are approximately 17% of the firm's total 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 estimated fixed costs could include both types of costs.

Compared to f_{os}^X, the fixed costs of ICT adoption are lower, as shown in column (2) of Table A.17. The average costs paid by firms adopting ICT range from \$1.16 million in the Pacific to \$1.45 million in the Middle Atlantic. These costs may include not only monetary expenses for purchasing hardware and software but also the forgone profits due to the time spent upgrading the system. These fixed costs rise in the location's average distance to the nearest NSFNET node, which measures local ICT access, with an elasticity of 0.121. As many small and single-unit firms also adopt an intranet in the data, there is large dispersion in the fixed costs of ICT adoption.

Model fit. The last column in Table 7 shows that the model is able to replicate the data moments well. To further validate the model, I compare the simulated bilateral expansion patterns, i.e., the share of firms that are headquartered in census division o and have establishments in census division s, to those shares from the data. Ideally, I would use the LBD to construct these moments. Unfortunately, these moments often have small sample sizes. Data privacy policies from the Census Bureau thus prevent me from disclosing these data. Therefore, I turn to an alternative dataset—the manufacturing package from the National Establishment Time Series (NETS) database—to calculate the bilateral expansion patterns. NETS is a comprehensive dataset that covers the universe of US establishments in the manufacturing and related sectors.[53] The database is comparable to the LBD in terms of its geographic coverage and firm ownership linkages. Figure 7 shows a high correlation of 0.76 between the model-simulated bilateral expansion patterns and the data patterns from NETS, adjusted by a constant share difference. These shares are affected not only by the estimates from the third step but also the local productivity estimated in the second step and the headquarters–establishment communication elasticities estimated in the first step. Overall, the model does a good job in matching the targeted and untargeted moments.

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[52] 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.

[53] Barnatchez et al. (2017) provide detailed assessments of the NETS database and compare it to confidential US Census data. Rossi-Hansberg et al. (2021) use the NETS database and document a diverging concentration at the local and national levels.

5 Efficiency Gains from ICT and Policy Implications

Using the estimated model, I quantify the efficiency gains from policies aimed at reducing ICT costs. I start by analyzing the Internet privatization in Section 4.2.2, one of the largest government ICT infrastructure projects in the US history, and clarifying the underlying mechanisms that drive the efficiency gains across locations. Then, I discuss the implications for policies improving ICT access and reducing digital divide. 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 ICT adoption to match my reduced-form estimate of a 2.56% increase in the average number of census divisions in which a firm operate, as reported in Section 4.2.2.[54] Since the model is estimated to match moments in 1999, the fixed costs of adopting ICT are estimated for the postprivatization economy. To back out prereform fixed costs, I use my reduced-form estimate to discipline the changes in the fixed costs, ensuring that the resulting change in the average number of census divisions per firm matches the 2.56% increase. To simulate the policy and match the reduced-form estimate, I use the partial equilibrium version of the model, fixing the equilibrium prices to those in the postprivatization equilibrium.[55] Other parameters are held constant. Recall that the fixed costs of ICT adoption are proportional to the average distance to NSFNET nodes. Thus, I raise the distance to nodes so as to increase ICT costs and obtain the prereform fixed costs of ICT adoption.

ICT costs are set to be 80% higher before the Internet privatization to match the 2.56% change in the firm's geographic scope. Given the associated average prereform costs μ^{ICT}_{pre}, I simulate the full model, allowing equilibrium prices to adjust accordingly. The overall ICT adoption rate is 19% lower compared to the benchmark model.

Figure 8 displays the efficiency gains, measured by changes in the inverse of local price indices, from the Internet privatization. Through the lens of the model, the aggregate production efficiency increased by around 1.3%.[56] The local efficiency gains range from 0.93% in the West

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[54] Column (3) in Table 3 Panel B shows that the estimated coefficient on the interaction term HQDistToNode × Post is -0.048. Taking into account that the average distance to 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 ($= 0.048 \times 130/100/2.439 \times 100\%$).

[55] The difference-in-differences regression in Equation (17) 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.

[56] I calculate aggregate efficiency gains by taking the average of local efficiency gains across locations, weighted by each location's consumption share.

South Central census division to 1.47% in the Pacific census division. Given an 80% decrease in the cost ICT adoption, these estimates indicate an elasticity of efficiency with respect to ICT cost between 0.012 and 0.018.

It is worth discussing the magnitude of the efficiency gains before examining the main mechanisms behind these estimates. Bureau of Labor Statistics reported a 9.4% increase in manufacturing productivity from 1996 to 2000, with an average annual growth rate at 1.8 percent.[57] This implies that the estimated efficiency gains account for over 10 percent of this overall post-1995 productivity growth. While the literature has extensively documented the positive relationship between ICT investment and usage with firm production efficiency, which significantly contributes to the post-1995 aggregate productivity growth in the US, there is no consensus on the sources of these efficiency gains.[58] Here, I propose a new source of efficiency gains from ICT by allowing firms to expand geographically. By discipline the effects of ICT using micro data on the relationship between firms' geographic operation and their ICT adoption, I find nontrivial efficiency gains that are greater than what would be without considering firms' geographic expansion.

5.1.1 Mechanisms

The aggregate and geographic distribution of efficiency gains is driven by three main mechanisms. First, firms can expand geographically by adopting better technologies, because of the reduced ICT costs. Second, better ICT reduces headquarters–establishment communication costs $d_{os}(\varphi)$. Third, better ICT 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 ICT cost decreases, more firms adopt better ICT that reduces both d_{os} and h, but firms do not reoptimize their establishment locations. Panel A in Figure 9 shows the corresponding efficiency gains (solid bars) and contrast with the benchmark results (clear bars). Without geographic expansion, the aggregate efficiency gain decreases from 1.3% to 0.8%, or about 40 percent lower. The decrease in efficiency gains varies across locations, ranging from an 18 percent drop in the South Atlantic to a 55 percent decrease in the Pacific.

These differences across locations highlight the importance of firms' reoptimizing their establishment locations in determining local efficiency gains. Appendix Table A.18 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

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[57] BLS reports annual total factor productivity for major industries: `https://www.bls.gov/productivity/tables/major-industry-total-factor-productivity-klems.xlsx`.

[58] 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 a crucial role in driving the post-1995 aggregate productivity growth in the US.

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 64% of local efficiency gains in the South Atlantic, while new entrants contribute around 17%. In contrast, new entrants contribute 56% to efficiency gains in the Pacific. Therefore, the Pacific is disproportionately affected when firms are not allowed to reoptimize their establishment locations. Overall, outside firms account for four-fifths of local local efficiency gains, while local firms account for the rest.[59]

To further isolate the effects of the two channels through which ICT improves production efficiency, I compute another counterfactual that further shuts down the internal communication channel. I do so by equalizing the elasticity of communication costs associated with high and low ICT levels, effectively setting $d_{os}(\overline{\varphi})$ to be the same as $d_{os}(\underline{\varphi})$. In this case, the only benefit from ICT adoption is a firm-wide productivity increase. Panel B in Figure 9 shows the corresponding efficiency gains. The aggregate efficiency gains further decreases from 0.8% to 0.58%, or 27 percent lower. Taken together, restricting the geographic expansion of firms and shutting down the internal communication channel of ICT results in a reduction of overall efficiency gains by nearly half.

5.2 Policies Reducing ICT Cost

Governments around the world continue to make significant investments in ICT, such as the recent Infrastructure Investment Bill and American Jobs Act (IIJA) in the US, 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 10 shows the averages of the estimated fixed costs of ICT adoption for each census division. The differences in ICT costs are driven by the location's average distance to NSFNET nodes. Consistent with the premise that the West Coast had better ICT infrastructure, firms in the Pacific census division had the lowest cost. In contrast, firms in the New England, Middle Atlantic, East South Central and West South Central census divisions faced higher costs. In the following, I simulate two policies that reduce the costs of ICT adoption—one at the local level and the other at the national level.

5.2.1 Local ICT Cost Reduction

I first simulate a local policy that reduces ICT cost by approximately 17% in the West South Central census division, including Arkansas, Louisiana, Oklahoma and Texas. For instance, local governments might expand and upgrade broadband infrastructure so that firms have better access to high-speed Internet and advanced business applications such as intranets. This cost reduction

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[59] Appendix D.1 provides more details on the decomposition of efficiency gains.

increases the local ICT adoption rate by 3.4%. Because of the complementarity between ICT adoption and geographic expansion, more local firms become multi-unit. Panel B of Figure 10 shows where those West South Central firms expand their production. The Middle and South Atlantic and Pacific census divisions are among the favorite destinations. Consistent with the model prediction, these locations are relatively far away but have high productivity or market access. The expansion patterns suggest that ICT infrastructure improvements in the South can affect remote regions through firms' expansion.

Panel C shows the distribution of local efficiency gains. As a direct effect, local efficiency in the West South Central census division increases by 0.023%.[60] Moreover, other locations benefit substantially from this local ICT cost reduction, ranging from 0.013% in the West North Central and the Pacific, which is half of the direct impact, to 0.009% the East North Central, leading to a 0.012% aggregate efficiency gain. The far-reaching effects could be attributed to two channels—trade and multi-unit production. To disentangle the operation of these two channels, I compare the benchmark model with an alternative model that shuts down the multi-unit production channel.[61] Panel D shows that a trade-only model would underestimate the geographic scope of the effects of a local cost reduction. The gains are geographically confined to the West South Central census division and decay rapidly in the distance. One key driver of the differences between the two models is the elasticity of communication costs and trade costs with respect to the distance. The estimated elasticity of communication costs is 0.072 and 0.181 for intranet adopters and nonadopters, respectively. Even for intranet nonadopters, which bear high costs of communication between establishments and headquarters, the elasticity is smaller than that of trade costs with respect to the distance. Therefore, firms' multi-unit production is an important channel through which a local shock can spill over across locations.

In Appendix D.1, I break down local efficiency gains into contributions from local and outside firms, highlighting the role of geographic expansion in shaping the distribution of efficiency gains across regions.

5.2.2 National ICT Cost Reduction

Consider an alternative policy by the federal government to lower the costs of ICT for all locations. To capture the notion of reducing 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 ICT cost: $|\Delta\mu^{ICT}| \propto \alpha \mathrm{HQ}\widetilde{\mathrm{DistTo}}\mathrm{Node}_o$, where $\mathrm{HQ}\widetilde{\mathrm{DistTo}}\mathrm{Node}_o$ is the average distance to the nearest NSFNET node in census division o. Parameter α is set such that the aggregate cost reduction

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[60] Together with the 17% drop in the cost of ICT, we can translate it into an elasticity of efficiency with respect to the ICT cost of approximately -0.0013.

[61] 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.

in this national policy is the same as that in the previous local policy. Put differently, the cost reduction from the local policy is split across locations, disproportionately favoring those with high ICT costs.

Panel A of Figure 11 shows the extent of the cost reduction for different regions, ranging from 3.8% in the New England to 0.13% in the Pacific. Panel B compares the resulting efficiency gains (solid bars) with those from the local policy (clear bars). Although the reduction in ICT costs varies across locations, the differences in efficiency gains are smaller primarily due to the spillover effects of multi-unit production. Even locations that experience smaller reductions in ICT costs, such as the Pacific, can see significant efficiency gains. On average, the national ICT cost reduction leads to an aggregate efficiency gain of 0.013%, which is around 8.5 percent higher than the local ICT cost reduction.[62]

Taken together, these results underscore the importance of taking multi-unit production into account when we evaluate the gains from ICT and policy proposals that lower ICT costs. A coordinated approach to reducing the digital divide across regions can lead to larger overall gains.

6 Conclusion

Recent developments in ICT have enabled firms to expand their production across locations. This paper provides empirical evidence and a quantitative framework to study the effects of ICT on firms' geographic organization and examines the implications for aggregate efficiency and policies aimed at broadening ICT access. The empirical part of the paper leverages US Census micro data and documents a positive relationship between firms' ICT adoption, internal communication, and geographic expansion.

In the quantitative part, I develop a spatial equilibrium model of multi-unit firm location choices and their ICT adoption. The model generates economies of scale by allowing firms to pay a fixed cost of adopting advanced ICT to (i) improve firm-wide productivity, and (ii) reduce the communication costs from the headquarters to other establishments, which gives rise to rich interaction between ICT adoption and firms' internal geography. ICT adoption and geographic expansion are complements to each other.

I estimate the model by matching firms' geographic expansion patterns and ICT adoption observed in the data. In particular, using a model-derived within-firm labor allocation equation, I estimate the elasticities of headquarters–establishment communication costs with respect to distance for firms with different technologies. The estimates show that ICT adoption reduce the

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[62] Bureau of Economic Analysis reports that manufacturing GDP in 1999 is 1,549.8 billion in 1999 US dollars. An increase of 0.013% is approximately 200 million US dollars. An equivalent policy of subsidizing firm ICT adoption would cost approximately 22 million US dollars to achieve the same increase in ICT adoption.

elasticity by over 50 percent. Additionally, ICT adoption also increases firm effective productivity by approximately 30 percent.

I use the model to investigate efficiency gains from ICT development and policies. First, the model estimates that a milestone in the history of US Internet development—the Internet privatization of 1995, which greatly reduced ICT costs—increased aggregate efficiency by 1.3%, with around forty percent of the increase is accounted for by firms' geographic expansion.

Finally, policy simulations suggest that a national policy can be more effective than local policies in improving ICT access and reducing digital divide. Compared to an alternative trade-only model, the efficiency gains from ICT improvements are more geographically dispersed when we take into account firms' multi-unit production and geographic expansion.

References

Aarland, K., J. C. Davis, J. V. Henderson, and Y. Ono (2007). Spatial organization of firms: The decision to split production and administration. *The RAND Journal of Economics 38*(2), 480–494.

Abadie, A. (2005). Semiparametric difference-in-differences estimators. *The Review of Economic Studies 72*(1), 1–19.

Aghion, P., A. Bergeaud, T. Boppart, P. J. Klenow, and H. Li (2019). A theory of falling growth and rising rents. Technical report, National Bureau of Economic Research.

Akerman, A., I. Gaarder, and M. Mogstad (2015). The skill complementarity of broadband internet. *The Quarterly Journal of Economics 130*(4), 1781–1824.

Akerman, A., E. Leuven, and M. Mogstad (2022). Information frictions, internet, and the relationship between distance and trade. *American Economic Journal: Applied Economics 14*(1), 133–63.

Antràs, P., E. Fadeev, T. C. Fort, and F. Tintelnot (2022). Global sourcing and multinational activity: A unified approach. Technical report, National Bureau of Economic Research.

Antras, P., T. C. Fort, and F. Tintelnot (2017). The margins of global sourcing: Theory and evidence from us firms. *American Economic Review 107*(9), 2514–64.

Aral, S., E. Brynjolfsson, and D. Wu (2006). Which came first, it or productivity? virtuous cycle of investment and use in enterprise systems. *Virtuous cycle of investment and use in enterprise systems*.

Arkolakis, C., F. Eckert, and R. Shi (2021). Combinatorial discrete choice.

Atalay, E., A. Hortaçsu, and C. Syverson (2014). Vertical integration and input flows. *American Economic Review 104*(4), 1120–48.

Barnatchez, K., L. D. Crane, and R. Decker (2017). An assessment of the national establishment time series (nets) database.

Baslandze, S. (2016). The role of the it revolution in knowledge diffusion, innovation and reallocation.

Bernard, A. B. and J. B. Jensen (2007). Firm structure, multinationals, and manufacturing plant deaths. *The Review of Economics and Statistics 89*(2), 193–204.

Bils, M. and P. J. Klenow (2000). Does schooling cause growth? *American economic review 90*(5), 1160–1183.

Bloom, N., L. Garicano, R. Sadun, and J. Van Reenen (2014). The distinct effects of information technology and communication technology on firm organization. *Management Science 60*(12), 2859–2885.

Bloom, N., R. Sadun, and J. Van Reenen (2012). Americans do it better: Us multinationals and the productivity miracle. *American Economic Review 102*(1), 167–201.

Bresnahan, T. (2010). General purpose technologies. In *Handbook of the Economics of Innovation*, Volume 2, pp. 761–791. Elsevier.

Brynjolfsson, E. and L. Hitt (1996). Paradox lost? firm-level evidence on the returns to information systems spending. *Management science 42*(4), 541–558.

Brynjolfsson, E. and L. M. Hitt (2003). Computing productivity: Firm-level evidence. *Review of economics and statistics 85*(4), 793–808.

Brynjolfsson, E. and S. Yang (1996). Information technology and productivity: a review of the literature. *Advances in computers 43*, 179–214.

Cao, D., H. R. Hyatt, T. Mukoyama, and E. Sager (2019). Firm growth through new establishments. *Available at SSRN*.

Chen, X., H. Hong, and A. Tarozzi (2008). Semiparametric efficiency in gmm models with auxiliary data. *The Annals of Statistics 36*(2), 808–843.

Dedrick, J., V. Gurbaxani, and K. L. Kraemer (2003). Information technology and economic performance: A critical review of the empirical evidence. *ACM Computing Surveys (CSUR) 35*(1), 1–28.

Disdier, A.-C. and K. Head (2008). The puzzling persistence of the distance effect on bilateral trade. *The Review of Economics and statistics 90*(1), 37–48.

Eaton, J. and S. Kortum (2002). Technology, geography, and trade. *Econometrica 70*(5), 1741–1779.

Eckert, F., S. Ganapati, and C. Walsh (2020). Skilled scalable services: The new urban bias in economic growth. *Available at SSRN 3736487*.

Fajgelbaum, P. D., E. Morales, J. C. Suárez Serrato, and O. Zidar (2019). State taxes and spatial misallocation. *The Review of Economic Studies 86*(1), 333–376.

Falck, O., R. Gold, and S. Heblich (2014). E-lections: Voting behavior and the internet. *American Economic Review 104*(7), 2238–65.

Forman, C., A. Goldfarb, and S. Greenstein (2003). The geographic dispersion of commercial internet use. *Rethinking rights and regulations: Institutional responses to new communication technologies*, 113–45.

Forman, C., A. Goldfarb, and S. Greenstein (2012). The internet and local wages: A puzzle. *American Economic Review 102*(1), 556–75.

Fort, T. C. (2017). Technology and production fragmentation: Domestic versus foreign sourcing. *The Review of Economic Studies 84*(2), 650–687.

Fort, T. C. and S. D. Klimek (2018, June). The Effects of Industry Classification Changes on US Employment Composition. Working Papers 18-28, Center for Economic Studies, U.S. Census Bureau.

Fort, T. C., J. R. Pierce, and P. K. Schott (2018). New perspectives on the decline of us manufacturing employment. *Journal of Economic Perspectives 32*(2), 47–72.

Frazer, K. D. (1996). *NSFNET: A partnership for high-speed networking: Final report, 1987-1995.* Merit Network.

Giroud, X. (2013). Proximity and investment: Evidence from plant-level data. *The Quarterly Journal of Economics 128*(2), 861–915.

Giroud, X., S. Lenzu, Q. Maingi, and H. Mueller (2021). Propagation and amplification of local productivity spillovers. Technical report, National Bureau of Economic Research.

Giroud, X. and H. M. Mueller (2019). Firms' internal networks and local economic shocks. *American Economic Review 109*(10), 3617–49.

Goldfarb, A. and C. Tucker (2019). Digital economics. *Journal of Economic Literature 57*(1), 3–43.

Greenstein, S. (2015). *How the internet became commercial: Innovation, privatization, and the birth of a new network.* Princeton University Press.

Greenstein, S. (2020). The basic economics of internet infrastructure. *Journal of Economic Perspectives 34*(2), 192–214.

Gumpert, A., H. Steimer, and M. Antoni (2022). Firm organization with multiple establishments. *The Quarterly Journal of Economics 137*(2), 1091–1138.

Guner, N., G. Ventura, and Y. Xu (2008). Macroeconomic implications of size-dependent policies. *Review of Economic Dynamics 11*(4), 721–744.

Hanlon, W. W., S. Heblich, F. Monte, and M. B. Schmitz (2022). A penny for your thoughts. Technical report, National Bureau of Economic Research.

Head, K. and T. Mayer (2014). Gravity equations: Workhorse, toolkit, and cookbook. In *Handbook of international economics*, Volume 4, pp. 131–195. Elsevier.

Hirano, K. and G. W. Imbens (2004). The propensity score with continuous treatments. *Applied Bayesian modeling and causal inference from incomplete-data perspectives 226164*, 73–84.

Hjort, J. and J. Poulsen (2019). The arrival of fast internet and employment in africa. *American Economic Review 109*(3), 1032–79.

Hsieh, C.-T. and E. Rossi-Hansberg (2019, June). The industrial revolution in services. Working Paper 25968, National Bureau of Economic Research.

Hu, K. and R. Shi (2019). Solving combinatorial discrete choice problems in heterogeneous agent models.

Jia, P. (2008). What happens when wal-mart comes to town: An empirical analysis of the discount retailing industry. *Econometrica 76*(6), 1263–1316.

Jiao, Y. and L. Tian (2019). Geographic fragmentation in a knowledge economy. Technical report, Working Paper.

Jorgenson, D. W. (2001). Information technology and the us economy. *American Economic Review 91*(1), 1–32.

Jorgenson, D. W., M. S. Ho, and K. J. Stiroh (2003). Growth of us industries and investments in information technology and higher education. *Economic Systems Research 15*(3), 279–325.

Jorgenson, D. W., M. S. Ho, and K. J. Stiroh (2008). A retrospective look at the us productivity growth resurgence. *Journal of Economic perspectives 22*(1), 3–24.

Juhász, R. and C. Steinwender (2018). Spinning the web: Codifiability, information frictions and trade. *NBER working paper*.

Kleinman, B. (2022). Wage inequality and the spatial expansion of firms. Technical report, mimeo.

Lashkari, D., A. Bauer, and J. Boussard (2018). Information technology and returns to scale. *Available at SSRN 3458604*.

Ma, Y. (2022). Specialization in a knowledge economy. *Available at SSRN 4052990*.

McKnight, L. W. and J. P. Bailey (1998). *Internet economics.* Mit Press.

Oberfield, E., E. Rossi-Hansberg, P.-D. Sarte, and N. Trachter (2020). Plants in space. Technical report, National Bureau of Economic Research.

Oliner, S. D. and D. E. Sichel (2000). The resurgence of growth in the late 1990s: is information technology the story? *Journal of economic perspectives 14*(4), 3–22.

Ramondo, N. and A. Rodríguez-Clare (2013). Trade, multinational production, and the gains from openness. *Journal of Political Economy 121*(2), 273–322.

Robins, J. M., M. A. Hernan, and B. Brumback (2000). Marginal structural models and causal inference in epidemiology. *Epidemiology 11*(5), 550–560.

Rossi-Hansberg, E., P.-D. Sarte, and N. Trachter (2021). Diverging trends in national and local concentration. *NBER Macroeconomics Annual 35*, 115–150.

Rubinton, H. (2020). The geography of business dynamism and skill biased technical change. *FRB St. Louis Working Paper* (2020-020).

Steinwender, C. (2018). Real effects of information frictions: When the states and the kingdom became united. *American Economic Review 108*(3), 657–96.

Stiroh, K. J. (2002). Information technology and the us productivity revival: what do the industry data say? *American Economic Review 92*(5), 1559–1576.

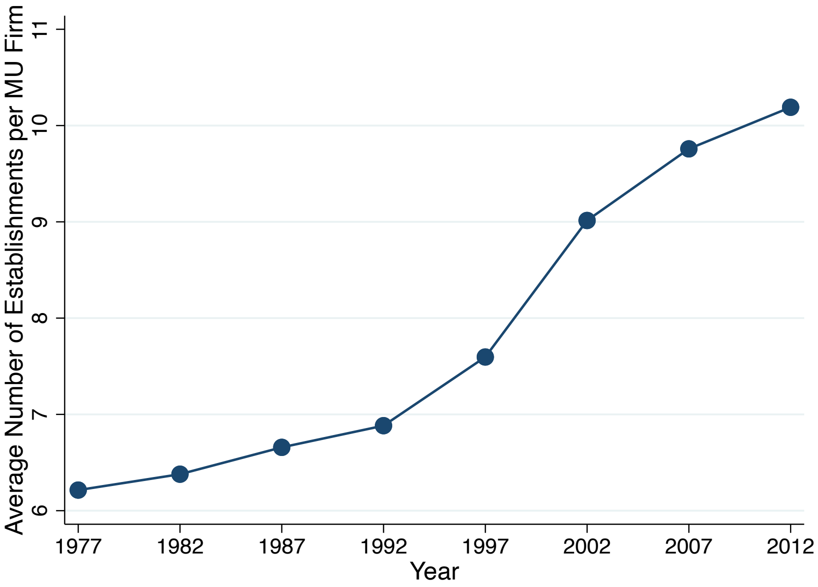
Tintelnot, F. (2017). Global production with export platforms. *The Quarterly Journal of Economics 132*(1), 157–209.

Van Reenen, J., N. Bloom, M. Draca, T. Kretschmer, R. Sadun, H. Overman, and M. Schankerman (2010). The economic impact of ict. *Final report*.

Van Reenen, J., M. Draca, and R. Sadun (2007). Productivity and icts: a review of the evidence.

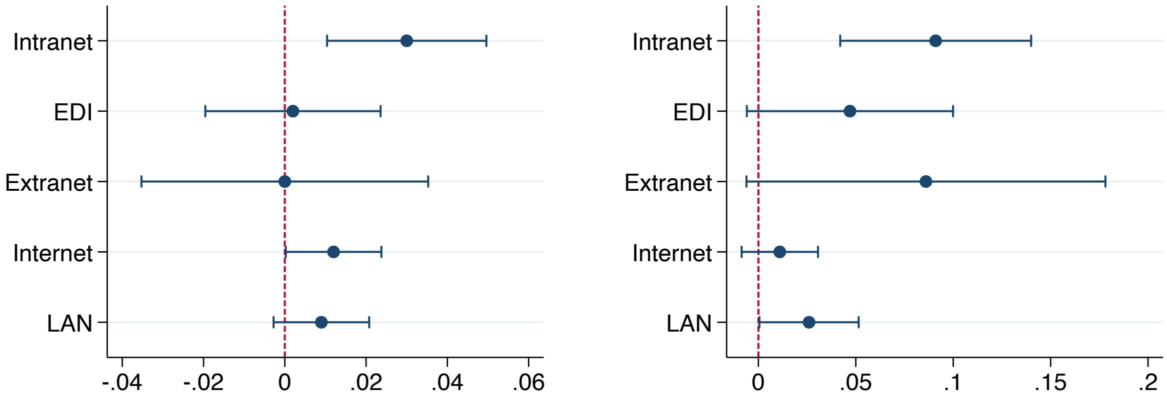
Wilson, D. J. (2009). Beggar thy neighbor? the in-state, out-of-state, and aggregate effects of r&d tax credits. *The Review of Economics and Statistics 91*(2), 431–436.

Figure 1: **Number of Establishments per Firm for Multi-Unit Firms from 1977 to 2012**

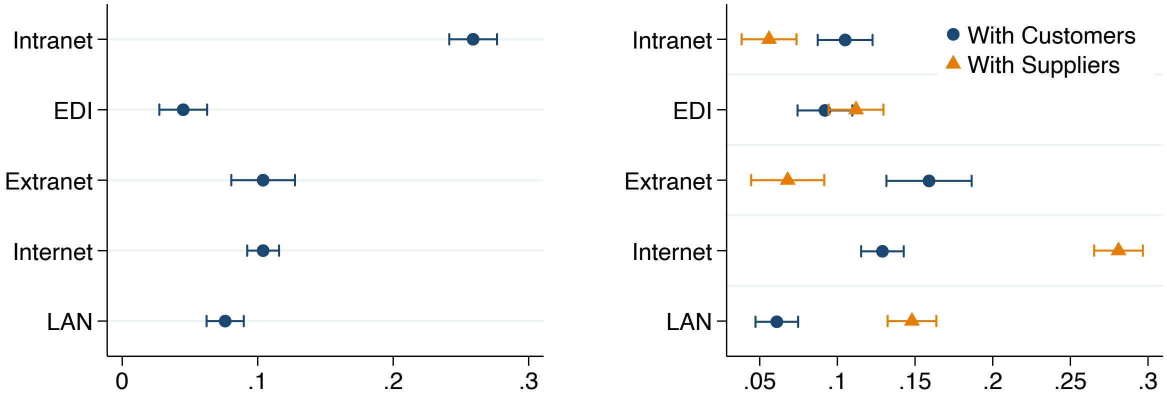


Notes: This figure plots the average number of establishments per firm for multi-unit firms in all sectors during 1977 and 2012, using the Longitudinal Business Database (LBD). Each firm is defined by a FIRMID–industry pair, where industry is at the six-digit NAICS level. Multi-unit firms are firms that operate more than one establishment in a certain industry. See Section 2 for details on data sources and construction of variables.

Figure 2: **ICT Adoption, Expansion, and Communication**


A. Number of Mfg. Establishments

B. Total Number of Establishments


C. Within-Firm Communication

D. External Communication

Notes: Panels A and B use the matched sample of the Longitudinal Business Database (LBD) and the Computer Network Use Supplement (CNUS) and plot the coefficients of a regression of the form:

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

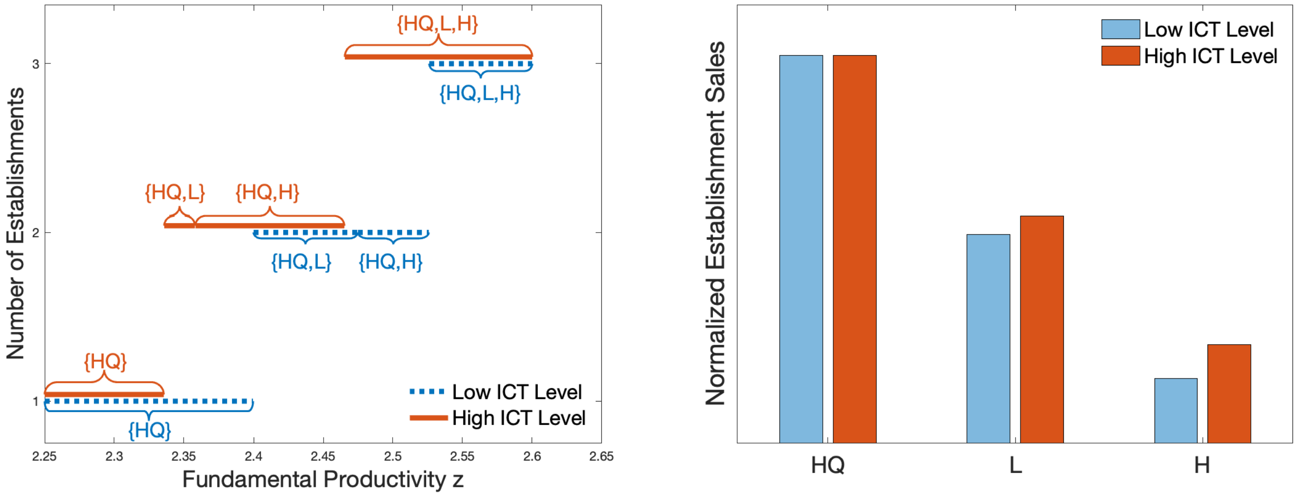
where the dependent variables $\Delta Y_{i,97-02}$ ($= \log Y_{i,02} - \log Y_{i,97}$) are the growth rate from 1997 to 2002 of firm i in the number of establishments per firm in the manufacturing sector (Panel A) and the total number of establishments per firm in all sectors (Panel B), respectively. Independent variables include indicators set to one if firm i adopted Intranet, Electronic data interchange (EDI), Extranet, Internet, and Local area network (LAN) by 1999. $X_{i,97}$ is a vector of 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. Confidence intervals are at the 95% level.

Panels C and D use the 1999 Computer Network Use Supplement (CNUS) sample and plot the coefficients of 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 (in Panel A), external customers (triangle markers in Panel B), and external suppliers (circle markers in Panel B), respectively. $X_{i,99}$ is a vector of firm characteristics in 1999, including the logarithm of capital to labor ratio, the logarithm of employment, the 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. Confidence intervals are at the 95% level.

Figure 3: **ICT and Firm Organization: An Illustration with Three Locations**

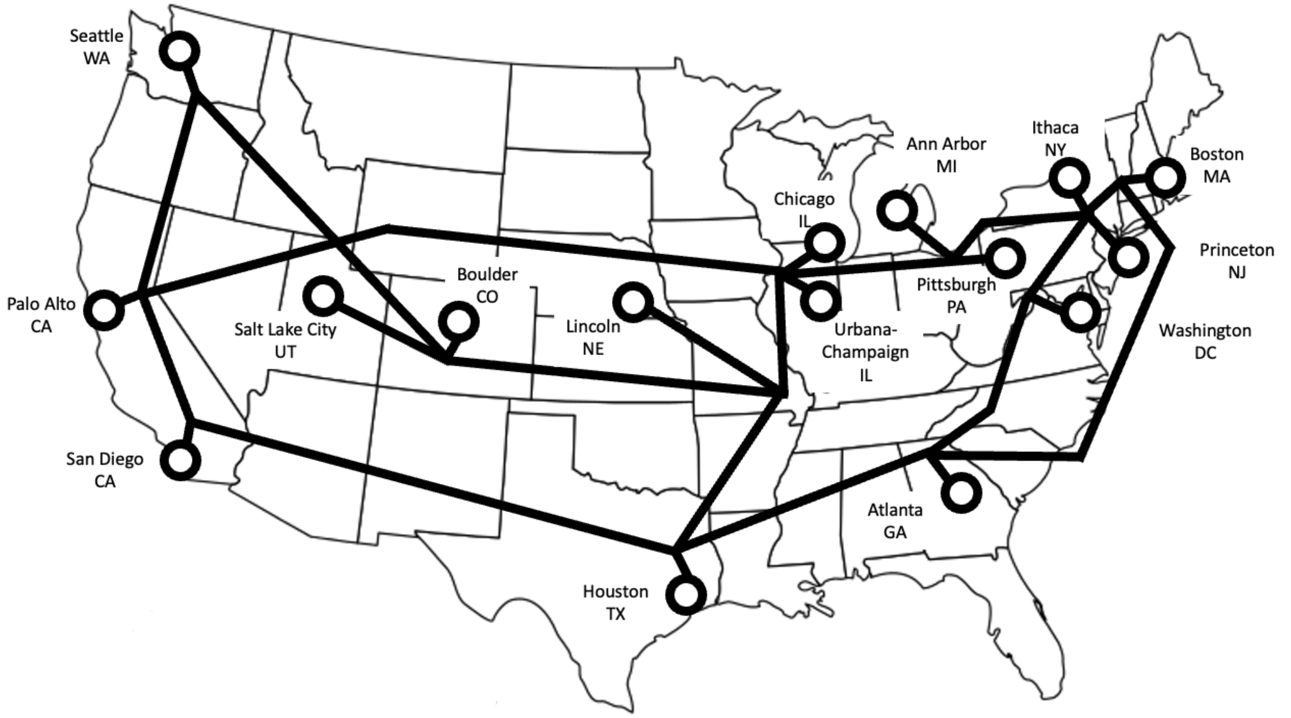


A. Extensive Margin: Location Choice

B. Intensive Margin: Establishment Sales Distribution

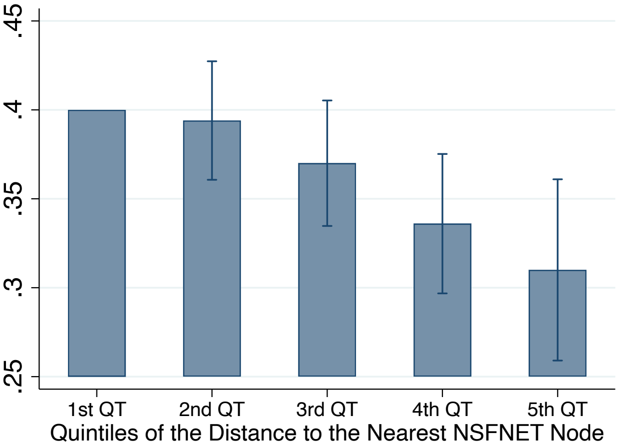
Notes: These figures depict the impacts of ICT adoption in a simple example with three locations $\{HQ, L, H\}$ and for firms headquartered in HQ. Panel A plots the number of establishments, along with the set of locations, against productivity for a low ICT level (the dotted line) and a high ICT level (the solid line), respectively. Panel B displays the sales of each establishment normalized by the sales of the headquarters for firms operating in all three locations in both low and high ICT levels. The light blue bars correspond to low ICT, while the solid orange bars correspond to high ICT. These figures are calculated using $\sigma = 4$, $\theta = 3.6$, $\overline{\varphi} = 1$, $\underline{\varphi} = 1.01$, $f_o^{ICT} = 0.5$, $f_{HQ,s}^X = (0, 1.31, 4.86)$, $T = (1, 1, 2)$, $E_s P_s^{\sigma-1} = (0.26, 0.21, 0.09)$. Distance is symmetric and equal to $\text{dist}_{HQ,L} = 1$, $\text{dist}_{HQ,H} = 2$, and $\text{dist}_{L,H} = 1.5$. Trade costs are $\log \tau_{sk} = 0.25 \log \text{dist}_{sk}$. Communication costs associated with low and high ICT are $\log d_{os}(\underline{\varphi}) = 0.16 \log \text{dist}_{os}$ and $\log d_{os}(\overline{\varphi}) = 0.145 \log \text{dist}_{os}$, respectively.

Figure 4: **Map of NSFNET in 1992**



Notes: This figure shows the NSFNET backbones and its node sites in 1992. The circles represent the exterior nodes at the following cities: Princeton (NJ), San Diego (CA), Champaign (IL), Ithaca (NY), Pittsburgh (PA), Boulder (CO), Salt Lake City (UT), Palo Alto (CA), Seattle (WA), Lincoln (NE), Houston (TX), Ann Arbor (MI), College Park (MD), Atlanta (GA), Argonne (IL) and Cambridge (MA). The black lines represent traffic flows on the network.

Figure 5: **Relationship between Distance to NSFNET Node and Intranet Adoption in 1999**

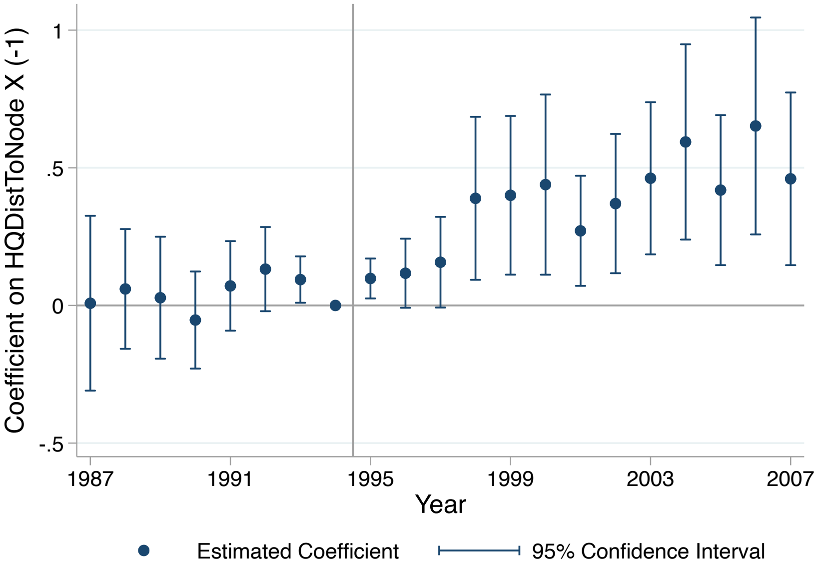


Notes: This figure uses the 1999 CNUS data and shows the relationship between firms' likelihood of adopting an intranet and their distance to the nearest NSFNET node. Particularly, I estimate a regression of the form:

$$\text{Intranet}_i = \sum_{k=1}^{5} \beta_k \mathbb{1}[\text{HQDistToNode}_i \in k\text{'s Quintile}] + \text{CountyControls}_i \gamma + \alpha_i^{\text{Industry}} + \alpha_i^{\text{State}} + \varepsilon_i,$$

where k denotes the quintile and $\mathbb{1}[\text{HQDistToNode}_i \in k\text{'th quintile}]$ is an indicator set to one if firm i's distance belongs to the k's quintile in the distribution. CountyControls_i is a vector of county characteristics, including the logarithm of the county's population and median household income, share of population below the poverty line, share of black population, share of population above 65 years old, and share of population with bachelor's degree. $\alpha_i^{\text{Industry}}$ and α_i^{State} are the industry and state fixed effect, respectively. Each bar represents the coefficient β_k and is normalized by the fraction of firms adopting Intranet in the first quintile.

Figure 6: **Reduced-Form Effects of Internet Privatization**

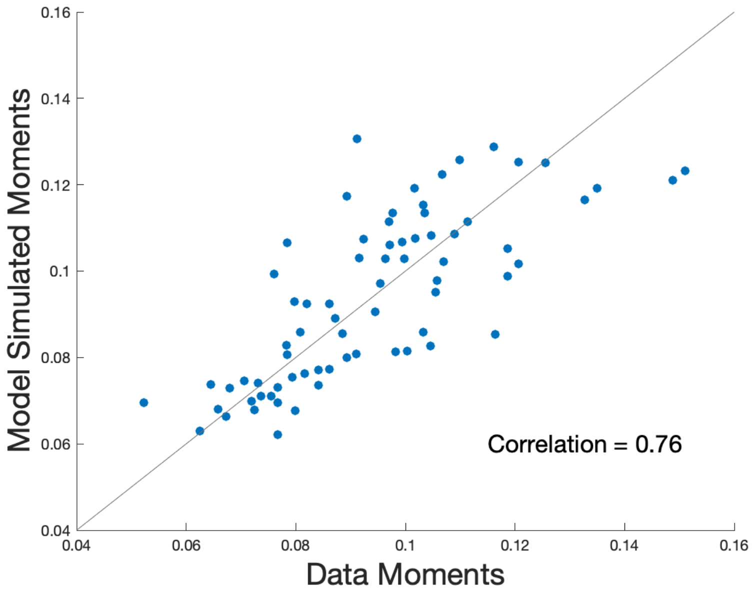


Notes: This figure uses the manufacturing firms in LBD from 1987 to 2007 and shows the effect of the Internet privatization on firms' geographic span of control by estimating a regression of the form:

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

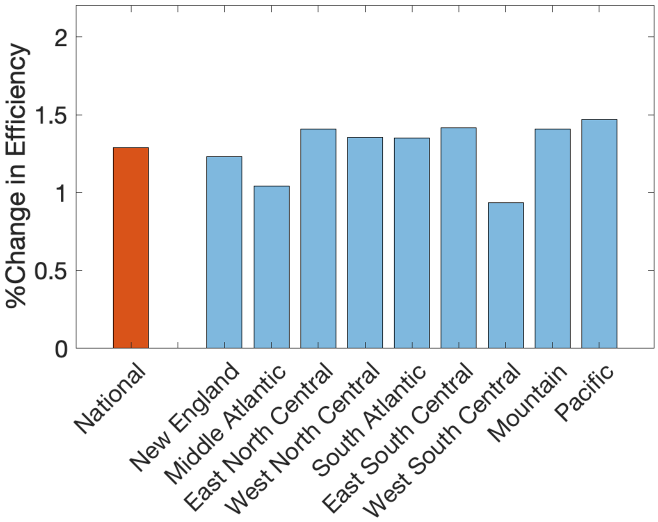
where the dependent variable is the number of establishments of firm i in year t and HQDistToNode_i is the distance from the firm's headquarters to the nearest NSFNET node. CountyControls_i is a vector of county characteristics, including the logarithm of the county's population and median household income, share of population below the poverty line, share of black population, share of population above 65 years old, and share of population with bachelor's degree. $\alpha_i^{\text{Industry-Year}}$ and $\alpha_i^{\text{State-Year}}$ are the industry–year and state–year fixed effect, respectively. The regression is weighted by firms' employment share. Standard errors are clustered at the firm and county level.

Figure 7: **Untargeted Moments: Bilateral Expansion Patterns**



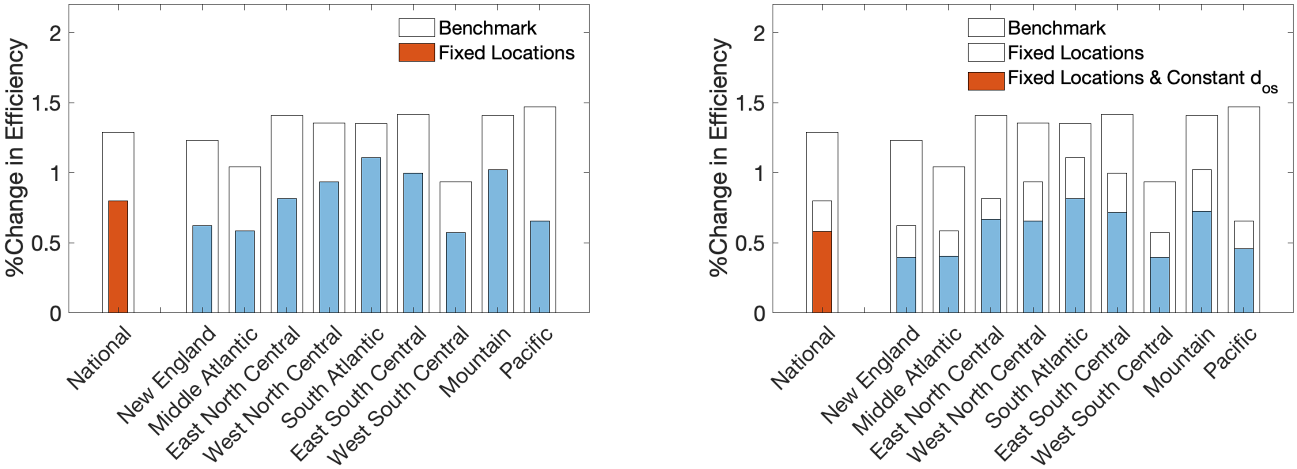
Notes: This figure plots the model-simulated shares of firms that expand from one census division to another against those shares calculated from the National Establishment Time Series (NETS) database. To account for the difference in average expansion shares in the LBD-CNUS matched sample and NETS database, I add a constant to the bilateral expansion shares from NETS.

Figure 8: Efficiency Gains from Internet Privatization



Notes: This figure 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). Local efficiency gains are measured as percentage changes in the local price indices. The aggregate efficiency gain is calculated by averaging the gains across locations, weighted by local consumption shares.

Figure 9: **Decomposing Efficiency Gains from Internet Privatization**

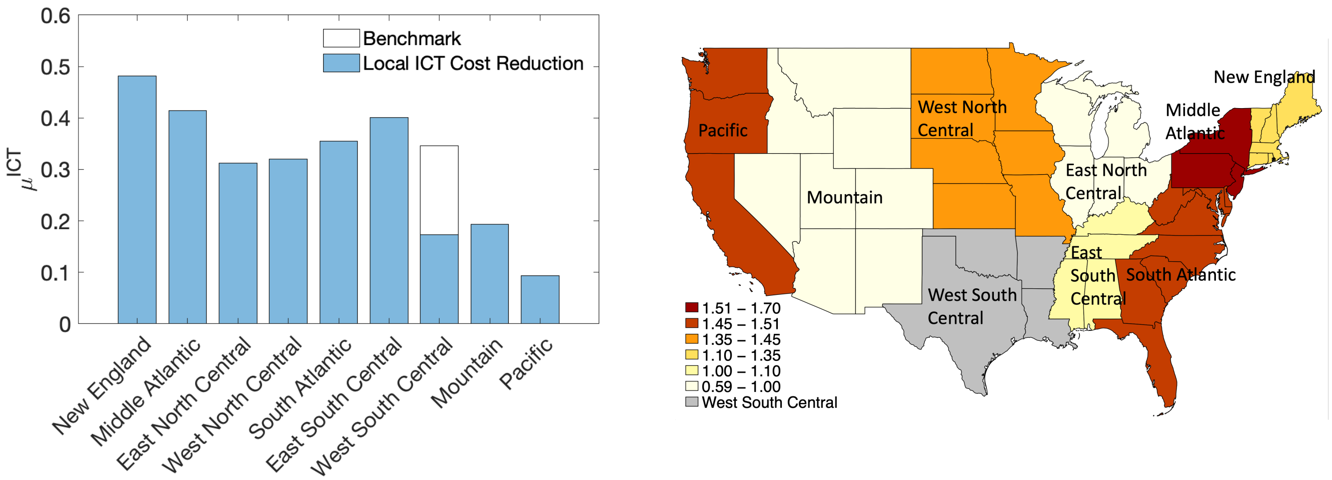

A. Fixing Locations

B. Further Shutting Down Internal Communication Channel

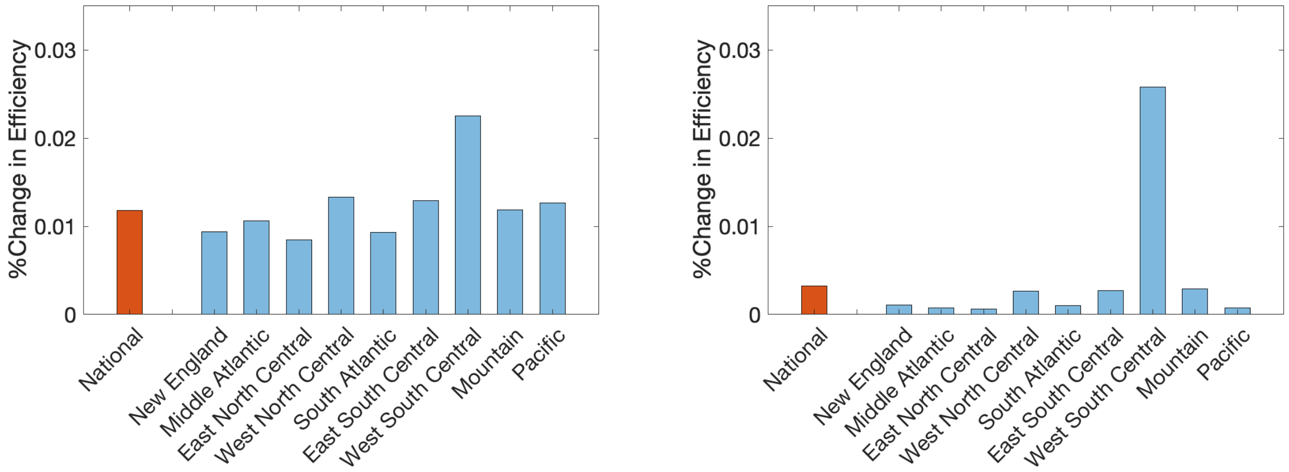
Notes: Panel A shows the efficiency gains from the Internet privatization when firms and their establishment locations are fixed (the solid bars) and contrasts to the benchmark results (the clear bars). Panel B further equalizes the headquarters–establishment communication costs (d_{os}) for low and high ICT firms, effectively shutting down the improvements in internal communication from ICT adoption.

Figure 10: **Local ICT Cost Reduction**

A. Logarithm of Average Fixed Costs of ICT B. %Changes in Establishment Locations

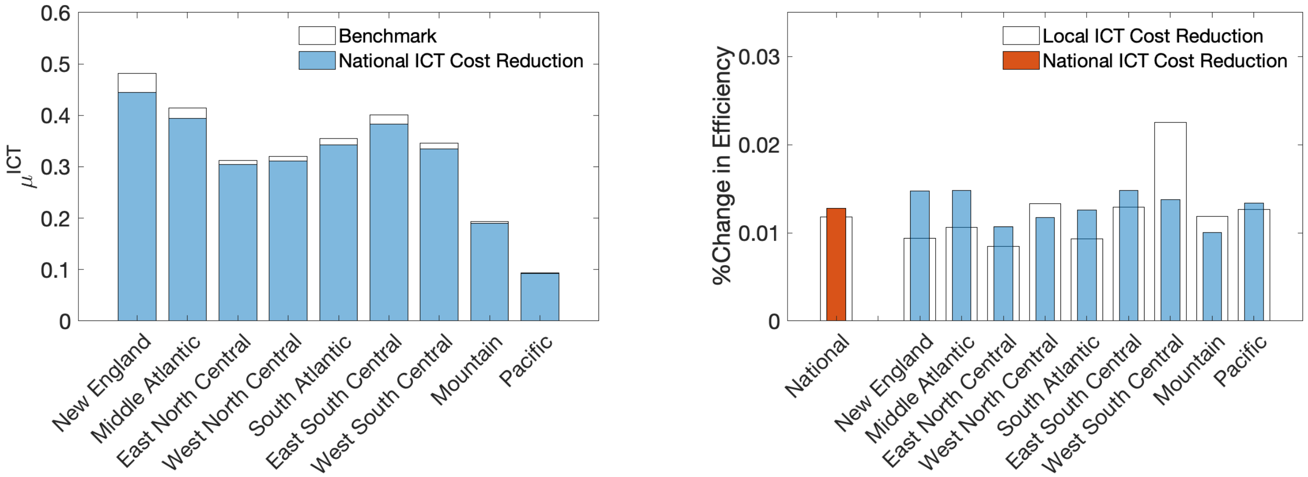


C. Efficiency Gains: Benchmark Model D. Efficiency Gains: Trade-Only Model



Notes: These figures show the changes from a policy simulation that reduces the fixed costs of ICT adoption in the West South Central census division. Panel A displays the logarithm of the average fixed costs of ICT adoption in each census division. Panel B presents the changes in the share of firms that expanded from the West South Central to the other census divisions. Panel C shows the efficiency gains in the benchmark model, while Panel D shows the gains in a trade-only model that shuts down the multi-unit production channel.

Figure 11: **National ICT Cost Reduction**


A. Logarithm of Average Fixed Costs of ICT

B. Efficiency Gains

Notes: These figures show the efficiency gains from a policy simulation that reduces the fixed cost of ICT adoption across all census divisions. Panel A displays the logarithm of the average fixed costs of ICT adoption in each census division, with locations that have 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 10 Panel C (the clear bars).

Table 1: **Summary Statistics**

	N	Mean	S.D.
A. 1977–2012 Longitudinal Business Database, Mfg., Census Years			
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
B. 1999 Computer Network Use Supplement			
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
Number of production workers	18,500	239.0	853.8
Salary and wages (in thousands)	18,500	12790	59530
Production workers wages (in thousands)	18,500	8125	42520
Sales (in thousands)	18,500	103200	829800
Capital (in thousands)	18,500	41350	233100

Notes: This table shows summary statistics of firms in the manufacturing sector from the Longitudinal Business Database (LBD, in Panel A) and firms in the Computer Network Use Supplement (CNUS) to the 1999 Annual Survey of Manufactures (in Panel B). Each firm is a FIRMID×6-digit NAICS industry pair. Panel A presents summary statistics for the LBD sample 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. Panel B presents summary statistics for firms' ICT adoption, communication patterns, and other firm characteristics for the 1999 CNUS data. Multi-unit firm is an indicator set to one if a firm has more than one establishment. Each variable regarding ICT adoption is an indicator set to one if the firm is connected to a type of network. Variables regarding communication are indicators set to one if the firm communicates with other company units, external customers, and external suppliers, respectively. Sales is total value of shipments. Capital is book value of fixed assets at the end of the year.

Table 2: **Summary of Parameters**

Parameter	Description	Value (S.E)
A. Assigned Parameters		
σ	Demand elasticity	4
θ	Dispersion of local productivity	3.6
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 communication 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 communication costs w.r.t distance with low ICT	0.181 (0.055)
β_1^d	ΔElasticity of communication 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 A.16
B.3 Step 3: Method of simulated moments		
$\underline{h}$	Firm-wide communication costs with low ICT	1.335 (0.172)
β_1^X	Intercept of avg. fixed costs of setting up establishments	1.733 (0.304)
β_2^X	Elasticity of avg. fixed costs of setting up establishments w.r.t distance	0.073 (0.046)
σ^X	Dispersion of fixed costs of setting up establishments	2.878 (0.146)
β_1^{ICT}	Intercept of avg. fixed costs of adopting ICT	1.289 (0.976)
β_2^{ICT}	Elasticity of avg. fixed costs of adopting ICT w.r.t. DistToNode	0.121 (0.082)
σ^{ICT}	Dispersion of fixed costs of adopting ICT	4.061 (0.646)

Notes: This table summarizes the model parameters. Panel A displays the parameters that are assigned (i.e., those not estimated). Panel B displays the parameters that are estimated in three steps. Standard errors are reported in the parentheses.

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 Establishments (4)	Non-Drivable Establishments (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

C. Characteristics of Locations for New Establishments

Average of	DistToNode (1)	Log Population (2)	Log Household Income (3)	%Age>65 (4)	%Bachelor's Degree (5)
HQDistToNode × Post	0.315**	-0.318	-0.087***	0.019***	-0.019
	(0.136)	(0.259)	(0.027)	(0.005)	(0.012)
N	1200	1200	1200	1200	1200
Avg. Dep. Var	1.574	12.36	10.47	0.125	0.206
County Controls	Y	Y	Y	Y	Y
Industry-Year FE	Y	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y	Y

Notes: This table uses the manufacturing firms in LBD from 1987 to 2007 and estimates regressions of the form:

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

where the dependent variable is a measure of the geographic span of control of firm i in year t, α_i is firm fixed effect, HQDistToNode_i is the distance from the ZIP code firm i is headquartered to its nearest NSFNET node (in 100 miles), and Post_t is an indicator set to one for years since 1995. $\alpha_i^{\text{Industry-Year}}$ and $\alpha_i^{\text{State-Year}}$ are industry–year and state–year fixed effects, respectively. The dependent variable in Panel A is the number of establishments a firm operates. Column (1) reports the baseline results. Column (2) includes county characteristics as additional controls. Column (3) restricts the sample to multi-unit firms. The regressions in column (1)–(3) are weighted by the firm's employment share. Column (4) reports the unweighted regression result. Column (5) is weighted by the inverse propensity scores detailed in Appendix Section C.3.1. 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. Panel C restricts to firms with new establishments. The dependent variables for columns (1)–(5) are the average distance from the new establishment's location to the nearest NSFNET node, and those locations' log population, log household income, the share of population older than 65, and the share of population with a bachelor's degree. Standard errors are clustered at the firm and headquarters county level. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 4: **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 variable in columns (1)–(4) is the firm's adoption of Intranet, Internet, Extranet, and Electronic data interchange (EDI), respectively. α_i is 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 5: **First-Step Estimation Results**

	Establishment Employment Share			
	All Years	Year 1999		
	OLS (1)	OLS (2)	OLS (3)	IV (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 presents the first-step estimation results. 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. Column (1) uses the LBD–CNUS matched sample from 1987 to 2007. Columns (2)–(4) use the 1999 subsample of the matched sample. Standard errors are clustered at the firm level. Standard errors using the instrumental variable approach in column (4) are calculated by 1,000 bootstrapped samples. The regressions are weighted by the weights provided in the 1999 Annual Survey of Manufactures. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 6: **Second-Step Regression Results**

	Purified Estimates of Census Division Fixed Effect		
	(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: The dependent variable is the census division fixed effect from 1987 to 2007 that is estimated in the first-stage regression and purged of local wages. The independent variables include the logarithm of R&D stocks and the logarithm of market access. 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. All regressions include the census fixed effect and year fixed effect. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 7: **Data and Model-Simulated Moments**

Moment	Data	Model
A. Expansion Patterns		
Share of multi-unit firms	0.343	0.343
Share of multi-unit firms with employment below median	0.020	0.025
Corr(%Firms$_{os}$, Log(Miles$_{os}$))	-0.369	-0.369
B. ICT Adoption Patterns		
Share of firms adopting Intranet	0.367	0.361
Share of firms adopting Intranet with employment below median	0.048	0.062
Corr(Intranet, Log(HQ$\widetilde{\text{DistToNode}}_o$))	-0.028	-0.029
C. Correlation of ICT Adoption and Multi-Unit Production		
Corr(Intranet, Multi-Unit)	0.555	0.559

Notes: This table compares the model simulated moments to data moments. Panel A includes moments that summarize firms' expansion patterns: the overall share of multi-unit firms, the share of multi-unit firms with employment below the median, and the correlation of the share of firms expanding from one census division to another and the logarithm of the distance (in miles) between the two census divisions. Panel B includes moments that summarize firms' ICT adoption patterns: the overall share of firms that have adopted an intranet, the share of adopting firms with employment below the median, and the correlation between a firm's ICT adoption and the logarithm of average distance to the nearest NSFNET node in the firm's headquarters census division, which is scaled by the census division's land area. Panel C is the correlation between a firm's intranet adoption and multi-unit status.

Online Appendix: Not for Publication

Appendix A describes additional details of the data, variable construction, and empirical motivation. Appendix B provides details of the model derivation. Appendix C outlines the structural estimation, including the institutional background of the Internet privatization and robustness checks for the reduced form analysis. Finally, Appendix D provides additional information for the policy simulation.

A Data and Empirical Motivation Appendix

I first outlines the procedure to identify firms' headquarters in Appendix Section A.1. Appendix A.2 clarifies the relationship between within-industry geographic expansion, the focus of this paper, and overall expansion. Appendix Section A.3 explains how to fit the increasing geographic expansion of multi-unit firms with the overall decline of the US manufacturing sector. Appendix Section A.4 shows robustness checks of the relationship between ICT adoption and firms' geographic expansion.

A.1 Identifying Firm Headquarters

Firms can be categorized into three types: (i) single-unit firms, (ii) multi-unit firms with stand-alone 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). As these firms have only one establishment, that establishment is considered the headquarters.

Second, to identify the stand-alone 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 but rather in management, supervision, general administrative functions, and supporting services for other establishments of the same enterprise, serving, for example, as 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 stand-alone headquarters of multi-unit firms. Before 1997, the AUX provides a detailed breakdown of 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 larger 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.[63] In this case, I use the 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, I choose the one with the largest payroll as the headquarters. The 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 multi-unit firms.

A.2 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 firm is related to that using FIRMID and then present robustness checks using alternative definitions in the next subsection.

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 that 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):

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

Now, denote a firm by a FIRMID–industry pair, i.e., $\tilde{i} = (i, j)$ and the number of firms at the FIRMID–industry level by $\tilde{N}^{\text{firm}}$. Then, we can get the second equality. To focus on the role of ICT in firms' within-industry expansion across locations, I focus on the first component by defining a firm by a FIRMID–industry pair, where the industry is at the six-digit NAICS level.

A.3 Span of Control for US Manufacturers

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

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[63] 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.

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. Meanwhile, it is well-documented that employment and the number of establishments of the manufacturing sector has 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 plots the average number of industries per FIRMID, which decreased over time.[64] 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.

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, 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 that 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. Firms that continue to operate in an industry throughout the period have been increasing their number of establishments, reflecting the 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) documents that the rising US 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.

A.4 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. Table A.11 column (1) 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 between 1997 and 2002.[65]. In this case, the definition of the firm is the same either way and the firm's scope is solely determined by their geographic scope. The results in

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

[65] Industry is defined at the six-digit NAICS level

column (2) show that the growth rate in the number of establishments is strongly correlated with intranet adoption, while other types of network adoption have weaker or no correlation.

Firms' 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. Column (3)–(5) in Table A.11 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 employment across all sectors, with intranet being the most strongly correlated with a firm's overall expansion. Column (5) shows that as firms expand into all sectors, they do not exhibit disproportionate expansion into nonmanufacturing sector. The correlation between the growth rate in the share of manufacturing employment and network adoption is economically small and statistically insignificant.

B Model Appendix

B.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). Denote the consumer's location by k, aggregate consumption by Y_k, and the expenditure by E_k. Denote the price index by P_k such that $E_k = P_k Y_k$. In each location, given the product prices (i.e., $p_{ok}(i, \omega)$) and total expenditure (i.e., E_k), the representative consumer maximizes her utility that aggregates all varieties with constant elasticity of substitution σ. We can express the consumer's problem as follows: in each location k,

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

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 Lagrangian is

$$\mathscr{L} = \left(\sum_{o=1}^{N} \int_0^{m_o} \int_0^1 y_{ok}(i,\omega)^{\frac{\sigma-1}{\sigma}} d\omega di \right)^{\frac{\sigma}{\sigma-1}} + \mu \left[E_k - \sum_{o=1}^{N} \int_0^{m_o} \int_0^1 p_{ok}(i,\omega) y_{ok}(i,\omega) d\omega di \right]$$

The first-order condition for each product is

$$Y_k^{-1/\sigma} y_{ok}(i,\omega)^{-1/\sigma} = \mu p_{ok}(i,\omega), \tag{22}$$

where $Y_k \equiv \left(\sum_{o=1}^{N}\int_0^{m_o}\int_0^1 y_{ok}(i,\omega)^{\frac{\sigma-1}{\sigma}}d\omega di\right)^{\frac{\sigma}{\sigma-1}}$. Then, we can express the expenditure on any product by the price and quantity of product ω of firm i headquartered in location o; that is, $p_{ok}(i',\omega')y_{ok}(i',\omega') = p_{ok}(i,\omega)y_{ok}(i,\omega)^{1/\sigma}y_{ok}(i',\omega')^{(\sigma-1)/\sigma}$. Thus, the total expenditure is

$$\begin{aligned}
&\sum_{o=1}^{N}\int_0^{m_o}\int_0^1 p_{ok}(i',\omega')y_{ok}(i',\omega')d\omega di\\
=&\sum_{o=1}^{N}\int_0^{m_o}\int_0^1 p_{ok}(i,\omega)y_{ok}(i,\omega)^{\frac{1}{\sigma}}y_{ok}(i',\omega')^{\frac{\sigma-1}{\sigma}}d\omega di\\
=&p_{ok}(i,\omega)y_{ok}(i,\omega)^{\frac{1}{\sigma}}Y_k^{\frac{\sigma-1}{\sigma}} = E_k, \qquad (23)
\end{aligned}$$

where the last equality follows the budget constraint. By definition of the price index, we can derive the demand for each product from location k:

$$y_{ok}(i,\omega) = E_k P_k^{\sigma-1}p_{ok}(i,\omega)^{-\sigma}. \qquad (24)$$

Integrating $y_{ok}(i,\omega)^{\frac{\sigma-1}{\sigma}}$ over (i,ω) and summing over the headquarters location o, we can get the price index for each location k: $P_k = \left(\sum_{o=1}^{N}\int_0^{m_o}\int_0^1 p_{ok}(i,\omega)^{1-\sigma}\right)^{1/(1-\sigma)}$.

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

This appendix section 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 the firm-specific productivity, S the set of establishment locations in which the firm operates, and φ the ICT level. As the production function has constant returns to scale and uses labor as the only input, the firm's unit cost of producing a variety ω at its establishment in 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 in 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 exists a representative consumer who makes consumption decisions independently. Due 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:

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

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

As the 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 cumulative distribution function of

$$P(p_{ok}(\omega,S,\varphi,z)\le p) = 1-e^{-\left(\frac{\sigma-1}{\sigma}\right)^\theta c^\theta z^\theta \Phi_{ok}(S,\varphi)}. \tag{25}$$

By the demand function in Equation (24), the sales of variety ω of the firm to market k is

$$\text{sales}_{ok}(\omega,S,\varphi,z) = p_{ok}(\omega,S,\varphi,z)y_{ok}(\omega,S,\varphi,z) = E_k P_k^{\sigma-1} p_{ok}(i,\omega)^{1-\sigma}, \forall\omega\in[0,1] \tag{26}$$

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

$$\begin{aligned}
\text{sales}_{ok}(S,\varphi,z) &= E_k P_k^{\sigma-1}\int_0^1 p_{ok}(i,\omega)^{1-\sigma}d\omega\\
&= \Gamma\left(\frac{\theta-\sigma+1}{\theta}\right)\left(\frac{\sigma-1}{\sigma}\right)^{\sigma-1}\left(\frac{z}{h(\varphi)}\right)^{\sigma-1} E_k P_k^{\sigma-1}\Phi_{ok}(S,\varphi)^{\frac{\sigma-1}{\theta}},
\end{aligned} \tag{27}$$

where E_k is the consumer's expenditure and P_k is the ideal price index in location k. Here, it is required that $\frac{\theta-\sigma+1}{\theta}>0$ to have a proper definition. It is worthwhile to note that 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,

$$\zeta_{ok\leftarrow s}(S,\varphi)\equiv\frac{\text{sales}_{ok\leftarrow s}(S,\varphi,z)}{\text{sales}_{ok}(S,\varphi,z)} = \frac{(T_s/w_s)^\theta d_{os}(\varphi)^{-\theta}\tau_{sk}^{-\theta}}{\Phi_{ok}(S,\varphi)}. \tag{28}$$

In the above expression, firms-specific components, including firm-wide productivity z and communication costs $h(\varphi)$, are canceled out.

Within-Firm Sales Distribution. Following Equation (28), we can get that the share of the firm's total sales generated by a nonheadquarters establishment at s is:

$$\begin{aligned}\zeta_{os}(S,\varphi) &= \frac{\sum_k \text{sales}_{ok\leftarrow s}(S,\varphi)}{\sum_k \text{sales}_{ok}(S,\varphi)} = \frac{\sum_k \text{sales}_{ok}(S,\varphi)\times\zeta_{ok\leftarrow s}(S,\varphi)}{\sum_k \text{sales}_{ok}(S,\varphi)} \\ &= (T_s/w_s)^{\theta} d_{os}(\varphi)^{-\theta}\sum_k\left(\frac{E_k P_k^{\sigma-1}\Phi_{ok}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}}{\sum_{k'} E_{k'}P_{k'}^{\sigma-1}\Phi_{ok'}(S,\varphi)^{\frac{\sigma-1}{\theta}}}\tau_{sk}^{-\theta}\right). \end{aligned} \tag{29}$$

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

$$\zeta_{oo}(S,\varphi) = \frac{\sum_k \text{sales}_{ok\leftarrow o}(S,\varphi)}{\sum_k \text{sales}_{ok}(S,\varphi)} = (T_o/w_o)^{\theta} d_{oo}(\varphi)^{-\theta}\sum_k\left(\frac{E_k P_k^{\sigma-1}\Phi_{ok}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}}{\sum_{k'} E_{k'}P_{k'}^{\sigma-1}\Phi_{ok'}(S,\varphi)^{\frac{\sigma-1}{\theta}}}\tau_{ok}^{-\theta}\right). \tag{30}$$

Combining Equations (29) and (30), we can derive the logarithm of the sales share at non-establishment locations $s \in S, s \neq o$, normalized by the logarithm of the headquarters sales share, as:

$$\begin{aligned}\log\tilde{\zeta}_{os}(S,\varphi) &\equiv \log\zeta_{os}(S,\varphi) - \log\zeta_{oo}(S,\varphi) \\ &= -\theta\log d_{os}(\varphi) + \log\left(\frac{\sum\omega_{ok}(S,\varphi)\tau_{sk}^{-\theta}}{\sum\omega_{ok}(S,\varphi)\tau_{ok}^{-\theta}}\right) + \theta\log(T_s/T_o) - \theta\log(w_s/w_o),\end{aligned} \tag{31}$$

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

Given the functional form of $d_{os}(\varphi) = e^{\beta^d(\varphi)\log \text{Miles}_{os}}$, we can get that

$$\log\tilde{\zeta}_{os}(S,\varphi) = -\theta\beta^d(\varphi)\log\text{Miles}_{os} + \log\left(\frac{\sum\omega_{ok}(S,\varphi)\tau_{sk}^{-\theta}}{\sum\omega_{ok}(S,\varphi)\tau_{ok}^{-\theta}}\right) + \theta\log(T_s/T_o) - \theta\log(w_s/w_o). \tag{32}$$

B.3 ICT Adoption and the Within-Firm Sales Distribution

This appendix section proves in the same three-location example as in the main text that ICT adoption increases the share of total sales generated by distant establishments.

Consider a simple case where there are three locations {HQ,L,H}. HQ represents the firm's headquarters location. Suppose that the firm has two establishments, its headquarters in *HQ* and another in *L*. The share of total sales that is generated by the firm's establishment in location $s \in \{HQ, L\}$ is:

$$\zeta_{HQ,s}(\{HQ,L\},\varphi) = \sum_k \left[\underbrace{\frac{E_k P_k^{\sigma-1}\big(\Phi_{HQ,k}(\{HQ,L\},\varphi)\big)^{\frac{\sigma-1}{\theta}}}{\sum_{k'} E_{k'} P_{k'}^{\sigma-1}\big(\Phi_{HQ,k'}(\{HQ,L\},\varphi)\big)^{\frac{\sigma-1}{\theta}}}}_{\substack{\text{Share of sales from market } k \\ \equiv B_{HQ,k}(\{HQ,L\},\varphi)}} \underbrace{\frac{(T_s/w_s)^{\theta} d_{HQ,s}(\varphi)^{-\theta}\tau_{sk}^{-\theta}}{\Phi_{HQ,k}(\{HQ,L\},\varphi)}}_{\substack{\text{Share of sales from market } k \\ \text{generated at establishment } s \\ \equiv \zeta_{HQ,k\leftarrow s}(\{HQ,L\},\varphi)}} \right],$$

where $\Phi_{HQ,k}(\{HQ,L\},\varphi) \equiv \sum_{s' \in \{HQ,L\}} (T_{s'}/w_{s'})^{\theta} d_{HQ,s'}(\varphi)^{-\theta}\tau_{s'k}^{-\theta}$ represents the production potential of the firm to market k. The first term captures the share of total sales from market k, and the second term captures the share of sales from market k that is accounted for by the establishment in location $s \in \{HQ, L\}$. Assume that trade costs are symmetric and satisfy the triangle inequality, and normalize the trade costs to one when the market is the same as the establishment location.[66]

Holding the firm's set of locations unchanged and equilibrium prices constant, I show that adopting better ICT increases the share of total sales by the establishment in L; that is,

$$\zeta_{HQ,L}(\{H,L\},\overline{\varphi}) > \zeta_{HQ,L}(\{H,L\},\underline{\varphi}).$$

<u>Derivation:</u> Denote the share of the firm's total sales from market k by $B_{HQ,k}(\{HQ,L\},\varphi)$ and, within the sales from market k, the share accounted for by the establishment at location $s \in \{HQ, L\}$ by $\zeta_{HQ,k\leftarrow s}(\{HQ,L\},\varphi)$. We can write the sales share of the establishment in L as:

$$\zeta_{HQ,L}(\{H,L\},\varphi) = \sum_{k=HQ,L,H} B_{HQ,k}(\{HQ,L\},\varphi) \times \zeta_{HQ,k\leftarrow L}(\{HQ,L\},\varphi)$$

For simplicity, I write the establishment location set $\{HQ, L\}$ as $(\cdot)$. The difference in the sales share of the establishment in L when it has high and low ICT levels is:

$$\begin{aligned}
\zeta_{HQ,L}(\cdot,\overline{\varphi}) - \zeta_{HQ,L}(\cdot,\underline{\varphi}) = & \sum_{k=HQ,L,H} \Big[B_{HQ,k}(\cdot,\overline{\varphi}) \times \zeta_{HQ,k\leftarrow L}(\cdot,\overline{\varphi}) - B_{HQ,k}(\cdot,\underline{\varphi}) \times \zeta_{HQ,k\leftarrow L}(\cdot,\overline{\varphi}) \\
& \quad + B_{HQ,k}(\cdot,\underline{\varphi}) \times \zeta_{HQ,k\leftarrow L}(\cdot,\overline{\varphi}) - B_{HQ,k}(\cdot,\underline{\varphi}) \times \zeta_{HQ,k\leftarrow L}(\cdot,\underline{\varphi}) \Big] \\
= & \sum_{k=HQ,L,H} \Big[B_{HQ,k}(\cdot,\underline{\varphi}) \times \underbrace{\Big(\zeta_{HQ,k\leftarrow L}(\cdot,\overline{\varphi}) - \zeta_{HQ,k\leftarrow L}(\cdot,\underline{\varphi})\Big)}_{\substack{\text{Change in the share of sales from market } k \\ \text{generated at establishment } L}} \Big] \\
& + \sum_{k=HQ,L,H} \Big[\underbrace{\Big(B_{HQ,k}(\cdot,\overline{\varphi}) - B_{HQ,k}(\cdot,\underline{\varphi})\Big)}_{\text{Change in the share of sales from market } k} \times \zeta_{HQ,k\leftarrow L}(\cdot,\overline{\varphi}) \Big] \qquad (33)
\end{aligned}$$

I first show that for any market k, adopting better ICT increases the share of sales from

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[66] That is, $\tau_{sk} = \tau_{ks}$, $\tau_{sk} < \tau_{sk'} \times \tau_{k'k}$, where $s, k, k' \in \{HQ, L, H\}$, and $\tau_{sk} = 1, s = k$.

that market that is generated at establishment L, which reflects improvements in production technology at establishment L. That is, the first summation term is positive.

Let market $k \in \{HQ, L, H\}$ be given. Then, we can obtain that

$$\begin{aligned}
\zeta_{HQ,k\leftarrow L}(\cdot,\overline{\varphi}) &= \frac{(T_L/w_L)^\theta d_{HQ,L}(\overline{\varphi})^{-\theta}\tau_{L,k}^{-\theta}}{(T_{HQ}/w_{HQ})^\theta \tau_{HQ,k}^{-\theta} + (T_L/w_L)^\theta d_{HQ,L}(\overline{\varphi})^{-\theta}\tau_{L,k}^{-\theta}} \\
&= \frac{1}{\left(\frac{T_{HQ}/w_{HQ}}{T_L/w_L}\right)^\theta \left(\frac{\tau_{HQ,k}}{\tau_{L,k}}\right)^{-\theta} d_{HQ,L}(\overline{\varphi})^\theta + 1} \\
&> \frac{1}{\left(\frac{T_{HQ}/w_{HQ}}{T_L/w_L}\right)^\theta \left(\frac{\tau_{HQ,k}}{\tau_{L,k}}\right)^{-\theta} d_{HQ,L}(\underline{\varphi})^\theta + 1} \equiv \zeta_{HQ,k\leftarrow L}(\cdot,\underline{\varphi}),
\end{aligned}$$

where we use the assumptions that $d_{HQ,HQ}(\overline{\varphi}) = d_{HQ,HQ}(\underline{\varphi}) = 1$ for the first equality and that $d_{HQ,L}(\overline{\varphi}) < d_{HQ,L}(\underline{\varphi})$ for the inequality. Thus, $\zeta_{HQ,k\leftarrow L}(\cdot,\overline{\varphi}) - \zeta_{HQ,k\leftarrow L}(\cdot,\underline{\varphi}) > 0$ for any market $k \in \{HQ, L, H\}$. Therefore, the first summation term is positive.

Now, before showing that the second summation is positive, I show a few properties.

Claim: The sales share of the establishment in L to each market, i.e., $\zeta_{HQ,k\leftarrow L}(\cdot,\varphi)$, satisfies the following relationship.

$$\zeta_{HQ,HQ\leftarrow L}(\cdot,\varphi) < \zeta_{HQ,H\leftarrow L}(\cdot,\varphi) < \zeta_{HQ,L\leftarrow L}(\cdot,\varphi), \text{ where } \varphi = \underline{\varphi}, \overline{\varphi}. \tag{34}$$

Derivation: Let the ICT level $\varphi \in \{\underline{\varphi}, \overline{\varphi}\}$ be given. By definition, we have that

$$\begin{aligned}
\zeta_{HQ,HQ\leftarrow L}(\cdot,\varphi) &= \frac{(T_L/w_L)^\theta d_{HQ,L}(\varphi)^{-\theta}\tau_{L,HQ}^{-\theta}}{(T_{HQ}/w_{HQ})^\theta \tau_{HQ,HQ}^{-\theta} + (T_L/w_L)^\theta d_{HQ,L}(\varphi)^{-\theta}\tau_{L,HQ}^{-\theta}} = \frac{1}{\left(\frac{T_{HQ}/w_{HQ}}{T_L/w_L}\right)^\theta \left(\frac{\tau_{HQ,HQ}}{\tau_{L,HQ}}\right)^{-\theta} d_{HQ,L}(\varphi)^\theta + 1} \\
\zeta_{HQ,L\leftarrow L}(\cdot,\varphi) &= \frac{(T_L/w_L)^\theta d_{HQ,L}(\varphi)^{-\theta}\tau_{L,L}^{-\theta}}{(T_{HQ}/w_{HQ})^\theta \tau_{HQ,L}^{-\theta} + (T_L/w_L)^\theta d_{HQ,L}(\varphi)^{-\theta}\tau_{L,L}^{-\theta}} = \frac{1}{\left(\frac{T_{HQ}/w_{HQ}}{T_L/w_L}\right)^\theta \left(\frac{\tau_{HQ,L}}{\tau_{L,L}}\right)^{-\theta} d_{HQ,L}(\varphi)^\theta + 1} \\
\zeta_{HQ,H\leftarrow L}(\cdot,\varphi) &= \frac{(T_L/w_L)^\theta d_{HQ,L}(\varphi)^{-\theta}\tau_{L,H}^{-\theta}}{(T_{HQ}/w_{HQ})^\theta \tau_{HQ,H}^{-\theta} + (T_L/w_L)^\theta d_{HQ,L}(\varphi)^{-\theta}\tau_{L,H}^{-\theta}} = \frac{1}{\left(\frac{T_{HQ}/w_{HQ}}{T_L/w_L}\right)^\theta \left(\frac{\tau_{HQ,H}}{\tau_{L,H}}\right)^{-\theta} d_{HQ,L}(\varphi)^\theta + 1}
\end{aligned}$$

Since $\tau_{HQ,H} < \tau_{HQ,L}\tau_{L,H}$ by the triangle inequality of trade costs and $\tau_{L,L} = 1$ by normalization, we have that $\frac{\tau_{HQ,L}}{\tau_{L,L}} > \frac{\tau_{HQ,H}}{\tau_{L,H}}$. Thus, we can obtain that $\zeta_{HQ,L\leftarrow L}(\cdot,\varphi) > \zeta_{HQ,H\leftarrow L}(\cdot,\varphi)$. Similarly, since $\tau_{L,H} < \tau_{L,HQ}\tau_{HQ,H}$ and $\tau_{HQ,HQ} = 1$, we can obtain that $\zeta_{HQ,HQ\leftarrow L}(\cdot,\varphi) < \zeta_{HQ,H\leftarrow L}(\cdot,\varphi)$.

Therefore, we have that $\zeta_{HQ,HQ\leftarrow L}(\cdot,\varphi) < \zeta_{HQ,H\leftarrow L}(\cdot,\varphi) < \zeta_{HQ,L\leftarrow L}(\cdot,\varphi)$ for $\varphi = \underline{\varphi}, \overline{\varphi}$.

Claim: Adopting better ICT increases the firm's production potential corresponding to market L relative to its production potential corresponding to markets HQ and H. That is,

$$\frac{\Phi_{HQ,L}(\cdot,\overline{\varphi})}{\Phi_{HQ,k}(\cdot,\overline{\varphi})} > \frac{\Phi_{HQ,L}(\cdot,\underline{\varphi})}{\Phi_{HQ,k}(\cdot,\underline{\varphi})}, \text{ where } k = HQ, H. \tag{35}$$

In addition, adopting better ICT increases the firm's production potential to market H relative to its production potential to market HQ. That is,

$$\frac{\Phi_{HQ,H}(\cdot,\overline{\varphi})}{\Phi_{HQ,HQ}(\cdot,\overline{\varphi})} > \frac{\Phi_{HQ,H}(\cdot,\underline{\varphi})}{\Phi_{HQ,HQ}(\cdot,\underline{\varphi})}. \tag{36}$$

<u>Derivation:</u> Note that $\Phi_{HQ,k}(\cdot,\overline{\varphi}) - \Phi_{HQ,k}(\cdot,\underline{\varphi}) = (T_L/w_L)^{\theta}[d_{HQ,L}(\overline{\varphi})^{-\theta} - d_{HQ,L}(\underline{\varphi})^{-\theta}]\tau_{L,k}^{-\theta}, k \in \{HQ, L, H\}$. Thus, improvements to the production potential corresponding to market k increase in the trade cost from establishment L to market k.

Let market $k \in \{HQ, H\}$ be given. We can show that

$$\begin{aligned}
&\frac{\Phi_{HQ,L}(\cdot,\overline{\varphi})}{\Phi_{HQ,k}(\cdot,\overline{\varphi})} - \frac{\Phi_{HQ,L}(\cdot,\underline{\varphi})}{\Phi_{HQ,k}(\cdot,\underline{\varphi})} \\
&\quad= \frac{\Phi_{HQ,L}(\cdot,\overline{\varphi})\Phi_{HQ,k}(\cdot,\underline{\varphi}) - \Phi_{HQ,L}(\cdot,\underline{\varphi})\Phi_{HQ,k}(\cdot,\overline{\varphi})}{\Phi_{HQ,k}(\cdot,\overline{\varphi})\Phi_{HQ,k}(\cdot,\underline{\varphi})} \\
&\quad= \frac{[\Phi_{HQ,L}(\cdot,\overline{\varphi}) - \Phi_{HQ,L}(\cdot,\underline{\varphi})]\Phi_{HQ,k}(\cdot,\underline{\varphi}) - \Phi_{HQ,L}(\cdot,\underline{\varphi})[\Phi_{HQ,k}(\cdot,\overline{\varphi}) - \Phi_{HQ,k}(\cdot,\underline{\varphi})]}{\Phi_{HQ,k}(\cdot,\overline{\varphi})\Phi_{HQ,k}(\cdot,\underline{\varphi})} \\
&\quad= \Bigg\{\left(\frac{T_L}{w_L}\right)^{\theta}\Big[d_{HQ,L}(\overline{\varphi})^{-\theta} - d_{HQ,L}(\underline{\varphi})^{-\theta}\Big]\tau_{L,L}^{-\theta}\Big[\left(\frac{T_{HQ}}{w_{HQ}}\right)^{\theta}\tau_{HQ,k}^{-\theta} + \left(\frac{T_L}{w_L}\right)^{\theta} d_{HQ,L}(\underline{\varphi})^{-\theta}\tau_{L,k}^{-\theta}\Big] \\
&\quad- \Big[\left(\frac{T_{HQ}}{w_{HQ}}\right)^{\theta}\tau_{HQ,L}^{-\theta} + \left(\frac{T_L}{w_L}\right)^{\theta} d_{HQ,L}(\underline{\varphi})^{-\theta}\tau_{L,L}^{-\theta}\Big]\left(\frac{T_L}{w_L}\right)^{\theta}\Big[d_{HQ,L}(\overline{\varphi})^{-\theta} - d_{HQ,L}(\underline{\varphi})^{-\theta}\Big]\tau_{L,k}^{-\theta}\Bigg\} \\
&\quad\times \frac{1}{\Phi_{HQ,k}(\cdot,\overline{\varphi})\Phi_{HQ,k}(\cdot,\underline{\varphi})} \\
&\quad= \frac{\left(\frac{T_L}{w_L}\right)^{\theta}\left(\frac{T_{HQ}}{w_{HQ}}\right)^{\theta}\Big[d_{HQ,L}(\overline{\varphi})^{-\theta} - d_{HQ,L}(\underline{\varphi})^{-\theta}\Big]\left(\tau_{HQ,k}^{-\theta} - \tau_{HQ,L}^{-\theta}\tau_{L,k}^{-\theta}\right)}{\Phi_{HQ,k}(\cdot,\overline{\varphi})\Phi_{HQ,k}(\cdot,\underline{\varphi})} > 0.
\end{aligned}$$

The last inequality follows from the facts that $d_{HQ,L}(\overline{\varphi}) < d_{HQ,L}(\underline{\varphi})$ and that the trade costs satisfy the triangle inequality. Similarly, we can show that

$$\frac{\Phi_{HQ,H}(\cdot,\overline{\varphi})}{\Phi_{HQ,HQ}(\cdot,\overline{\varphi})} - \frac{\Phi_{HQ,H}(\cdot,\underline{\varphi})}{\Phi_{HQ,HQ}(\cdot,\underline{\varphi})} > 0.$$

<u>Claim:</u> Adopting better ICT increases the share of sales from market L but decreases the share of sales from market HQ. That is,

$$B_{HQ,L}(\cdot,\overline{\varphi}) > B_{HQ,L}(\cdot,\underline{\varphi}), \tag{37}$$

$$B_{HQ,HQ}(\cdot,\overline{\varphi}) < B_{HQ,HQ}(\cdot,\underline{\varphi}). \tag{38}$$

Derivation: Denote $D_k = E_k P_k^{\sigma-1}, k = HQ, L, H$. By definition, we have that

$$\begin{aligned}
B_{HQ,L}(\cdot,\overline{\varphi}) &= \frac{D_L\big(\Phi_{HQ,L}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}}}{\sum_{k=HQ,L,H} D_k\big(\Phi_{HQ,k}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}}} \\
&= \frac{D_L\big(\Phi_{HQ,L}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}}}{D_{HQ}\big(\Phi_{HQ,HQ}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}} + D_L\big(\Phi_{HQ,L}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}} + D_H\big(\Phi_{HQ,H}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}}} \\
&= \frac{1}{\frac{D_{HQ}}{D_L}\left(\frac{\Phi_{HQ,HQ}(\cdot,\overline{\varphi})}{\Phi_{HQ,L}(\cdot,\overline{\varphi})}\right)^{\frac{\sigma-1}{\theta}} + 1 + \frac{D_H}{D_L}\left(\frac{\Phi_{HQ,H}(\cdot,\overline{\varphi})}{\Phi_{HQ,L}(\cdot,\overline{\varphi})}\right)^{\frac{\sigma-1}{\theta}}} \\
&> \frac{1}{\frac{D_{HQ}}{D_L}\left(\frac{\Phi_{HQ,HQ}(\cdot,\underline{\varphi})}{\Phi_{HQ,L}(\cdot,\underline{\varphi})}\right)^{\frac{\sigma-1}{\theta}} + 1 + \frac{D_H}{D_L}\left(\frac{\Phi_{HQ,H}(\cdot,\underline{\varphi})}{\Phi_{HQ,L}(\cdot,\underline{\varphi})}\right)^{\frac{\sigma-1}{\theta}}} \equiv B_{HQ,L}(\cdot,\underline{\varphi}),
\end{aligned}$$

where the inequality follows from inequality (35). Similarly, we can write the sales share from market HQ with high ICT as

$$\begin{aligned}
B_{HQ,HQ}(\cdot,\overline{\varphi}) &= \frac{D_{HQ}\big(\Phi_{HQ,HQ}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}}}{\sum_{k=HQ,L,H} D_k\big(\Phi_{HQ,k}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}}} \\
&= \frac{D_{HQ}\big(\Phi_{HQ,HQ}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}}}{D_{HQ}\big(\Phi_{HQ,HQ}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}} + D_L\big(\Phi_{HQ,L}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}} + D_H\big(\Phi_{HQ,H}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}}} \\
&= \frac{1}{1 + \frac{D_L}{D_{HQ}}\left(\frac{\Phi_{HQ,L}(\cdot,\overline{\varphi})}{\Phi_{HQ,HQ}(\cdot,\overline{\varphi})}\right)^{\frac{\sigma-1}{\theta}} + \frac{D_H}{D_{HQ}}\left(\frac{\Phi_{HQ,H}(\cdot,\overline{\varphi})}{\Phi_{HQ,HQ}(\cdot,\overline{\varphi})}\right)^{\frac{\sigma-1}{\theta}}} \\
&< \frac{1}{1 + \frac{D_L}{D_{HQ}}\left(\frac{\Phi_{HQ,L}(\cdot,\underline{\varphi})}{\Phi_{HQ,HQ}(\cdot,\underline{\varphi})}\right)^{\frac{\sigma-1}{\theta}} + \frac{D_H}{D_{HQ}}\left(\frac{\Phi_{HQ,H}(\cdot,\underline{\varphi})}{\Phi_{HQ,HQ}(\cdot,\underline{\varphi})}\right)^{\frac{\sigma-1}{\theta}}} \equiv B_{HQ,HQ}(\cdot,\underline{\varphi})
\end{aligned}$$

where the inequality follows from inequalities (35) and (36).

Finally, we can show that the second summation in Equation (33) is positive. Denote the change in the sales share from market k by $\Delta B_{HQ,k}(\cdot) \equiv B_{HQ,k}(\cdot,\overline{\varphi}) - B_{HQ,k}(\cdot,\underline{\varphi})$, $k \in \{HQ, L, H\}$. Since the total sales shares sum up to 1, i.e., $\sum_{k=HQ,L,H} B_{HQ,k}(\cdot,\varphi) = 1$, we have that $\Delta B_{HQ,H}(\cdot) = -\Delta B_{HQ,HQ}(\cdot) - \Delta B_{HQ,L}(\cdot)$. Then, we can write the second term in Equation (33) as:

$$\begin{aligned}
&\sum_{k=HQ,L,H}\left[\Big(B_{HQ,k}(\cdot,\overline{\varphi}) - B_{HQ,k}(\cdot,\underline{\varphi})\Big) \times \zeta_{HQ,k\leftarrow L}(\cdot,\overline{\varphi})\right] \\
&= \Delta B_{HQ,HQ}(\cdot) \times \zeta_{HQ,HQ\leftarrow L}(\cdot,\overline{\varphi}) + \Delta B_{HQ,L}(\cdot) \times \zeta_{HQ,L\leftarrow L}(\cdot,\overline{\varphi}) + \Delta B_{HQ,H}(\cdot) \times \zeta_{HQ,H\leftarrow L}(\cdot,\overline{\varphi}) \\
&= \underbrace{\Delta B_{HQ,HQ}(\cdot)}_{<0}\underbrace{[\zeta_{HQ,HQ\leftarrow L}(\cdot,\overline{\varphi}) - \zeta_{HQ,H\leftarrow L}(\cdot,\overline{\varphi})]}_{<0} + \underbrace{\Delta B_{HQ,L}(\cdot)}_{>0}\underbrace{[\zeta_{HQ,L\leftarrow L}(\cdot,\overline{\varphi}) - \zeta_{HQ,H\leftarrow L}(\cdot,\overline{\varphi})]}_{>0} > 0
\end{aligned}$$

By inequalities (38) and (37), we have that $\Delta B_{HQ,HQ}(\cdot) < 0$ and $\Delta B_{HQ,L}(\cdot) > 0$. By the relationship of the sales share of the establishment in L to each market in (34), we have that $\zeta_{HQ,HQ\leftarrow L}(\cdot,\overline{\varphi}) - \zeta_{HQ,H\leftarrow L}(\cdot,\overline{\varphi}) < 0$ and $\zeta_{HQ,L\leftarrow L}(\cdot,\overline{\varphi}) - \zeta_{HQ,H\leftarrow L}(\cdot,\overline{\varphi}) > 0$. Thus, the summation term is positive.

Hence, we have that adopting better ICT increases the sales share of the establishment in L. Thanks to CES demand and monopolistic competition, wage payments are proportional to sales. With wage rates held constant, employment is proportional to sales. Therefore, adopting better ICT increases the employment share at the establishment in L.

B.4 ICT Adoption and Geographic Expansion: Complementarity

This appendix section demonstrates a key feature of the model—the complementarity between technological upgrading and geographical expansion—in the same example with three locations.

Consider a single-unit firm deciding whether to expand its production to other locations.

Benefits of expanding are larger for firms with better ICT. The firm has four combinations of establishment locations: keeping production local (i.e., $\{HQ\}$), expanding to one of the other locations (i.e., $\{HQ, H\}$ or $\{HQ, L\}$), and expanding to both locations (i.e., $\{HQ, H, L\}$). The firm compares the cost and benefits of each combination. For example, a firm would like to add an establishment at L if and only if the additional gross profit exceeds the fixed cost of setting up the establishment there:

$$\begin{aligned}
&\sum_{k=1}^{N}\pi_{ok}(\{HQ,L\},\varphi,z) - \sum_{k=1}^{N}\pi_{ok}(\{HQ\},\varphi,z) \\
&= \frac{\sigma^{-\sigma}}{(\sigma-1)^{1-\sigma}}\tilde{\Gamma}\left(\frac{z}{h(\varphi)}\right)^{\sigma-1}\sum_{k} E_k P_k^{\sigma-1}\underbrace{\left((\Phi_{HQ,k}(\{HQ,L\},\varphi))^{\frac{\sigma-1}{\theta}} - (\Phi_{HQ,k}(\{HQ\},\varphi))^{\frac{\sigma-1}{\theta}}\right)}_{\text{Expansion increases production potential}} \geq f^{X}_{HQ,L}.
\end{aligned}$$

The left-hand side is the benefit of expanding to location L, i.e., the difference in gross profits by Equation (10); the right-hand side is the fixed cost of setting up an establishment at L for a firm headquartered at HQ. The benefit is positive because the production potential $\Phi_{ok}(S,\varphi)$ increases as firms set up more establishments. High ICT increases this benefit of geographic expansion through two channels. First and foremost, the difference in production potential is larger for firms with better ICT, as ICT improves the production efficiency of nonheadquarters establishments by reducing the costs of communication with the headquarters.[67] Second,

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[67] In this case, denote the increase in production potential by $\Delta(\varphi) \equiv (\Phi_{HQ,k}(\{HQ,L\},\varphi))^{\frac{\sigma-1}{\theta}} - (\Phi_{HQ,k}(\{HQ\},\varphi))^{\frac{\sigma-1}{\theta}} = \left(T_{HQ}^{\theta}(w_{HQ}\tau_{HQ,k})^{-\theta} + T_{L}^{\theta}(w_L\tau_{L,k}d_{HQ,L}(\varphi))^{-\theta}\right)^{\frac{\sigma-1}{\theta}} - \left(T_{HQ}^{\theta}(w_{HQ}\tau_{HQ,k})^{-\theta}\right)^{\frac{\sigma-1}{\theta}}$, where $k \in \{HQ, L, H\}$. Since ICT reduces communication costs between the headquarters and establishments, i.e., $d_{HQ,L}(\overline{\varphi}) < d_{HQ,L}(\underline{\varphi})$, and $(\sigma-1)/\theta > 0$, we can obtain that the increase in production potential for any market is larger for a firm with better ICT.

ICT increases the firm's effective productivity $\tilde{z} \equiv z/h(\varphi)$, which further raises the benefit of expanding.

Benefits of adopting ICT are larger for firms with a larger set of locations. A firm would like to upgrade to high ICT if and only if the benefit exceeds the fixed cost of adopting ICT; that is,

$$\begin{aligned}\sum_{k=1}^{N} \pi_{ok}(S, \overline{\varphi}, z) - \sum_{k=1}^{N} \pi_{ok}(S, \underline{\varphi}, z) = & \frac{\sigma^{-\sigma}}{(\sigma-1)^{1-\sigma}} \tilde{\Gamma} \Bigg\{ \underbrace{\left[\left(\frac{z}{h(\overline{\varphi})} \right)^{\sigma-1} - \left(\frac{z}{h(\underline{\varphi})} \right)^{\sigma-1} \right] \sum_{k=1} E_k P_k^{\sigma-1} \Phi_{HQ,k}(S, \overline{\varphi})^{\frac{\sigma-1}{\theta}}}_{\text{ICT adoption increases firm's effective productivity}} \\ & + \underbrace{\left(\frac{z}{h(\underline{\varphi})} \right)^{\sigma-1} \sum_{k=1} E_k P_k^{\sigma-1} \left(\Phi_{HQ,k}(S, \overline{\varphi})^{\frac{\sigma-1}{\theta}} - \Phi_{HQ,k}(S, \underline{\varphi})^{\frac{\sigma-1}{\theta}} \right)}_{\text{ICT increases production potential}} \Bigg\} \geq f_{HQ}^{ICT}.\end{aligned}$$

Both benefits of adopting ICT—increasing effective productivity and improving production potential—increase in the set of locations.[68] Therefore, all else held constant, firms with larger sets of locations are more likely to adopt ICT.

B.5 ICT Cost Reduction and Firm Location Choices

This appendix section 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 due to 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 A.5 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 3. The black fragment corresponds to the productivity range in which firms maintain a low ICT level, and the red fragment corresponds

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[68] First, the production potential increases in the set of establishments S, so the benefit from higher effective productivity is larger following the firm's expansion. Second, the benefit from the increasing production potential is larger when a firm includes additional establishments. Take the same example in which a firm either produces locally with $S = \{HQ\}$ or expands to another location with $S = \{HQ, L\}$. The benefit from the production potential is zero for the former case but is strictly positive for the latter, as the communication costs decrease. Nonheadquarters establishments always benefit from lower communication costs with the headquarters.

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 representing 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 due 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 to 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.

B.6 ICT Cost Reduction and Local Efficiency

This appendix section clarifies different channels through which ICT affects local efficiency, by decomposing local efficiency, reflected in the local price index, into the contributions from different types of firms.

Let location s be given. Denote the local price index by P_s, which can be written as follows.

$$
\begin{aligned}
P_s = \frac{\sigma}{\sigma-1}\tilde{\Gamma}^{\frac{1}{1-\sigma}} \Bigg\{ & \int_Z \mathbb{1}[\{s\} = S_s(\varphi(z), z)] \Big(\frac{h(\varphi(z))}{z}\Big) \underbrace{(T_s/w_s)^{-(1-\sigma)}}_{\text{Channel 1}} d\mu_s(z) \\
& + \int_Z \underbrace{\mathbb{1}[\{s\} \subset S_s(\varphi(z), z)]}_{\text{Channel 4}} \Big(\frac{h(\varphi(z))}{z}\Big) \Bigg[\underbrace{(T_s/w_s)^{\theta}}_{\text{Channel 1}} + \underbrace{\sum_{\substack{s' \in S_s(\varphi(z), z) \\ s' \neq s}} (T_{s'}/w_{s'})^{\theta} (d_{ss'}(\varphi(z)) \tau_{s's})^{-\theta}}_{\text{Channel 4}} \Bigg]^{-\frac{1-\sigma}{\theta}} d\mu_s(z) \\
& + \sum_{o \neq s} \int_Z \underbrace{\mathbb{1}[s \in S_o(\varphi(z), z)]}_{\text{Channel 3(b)}} \Big(\frac{h(\varphi(z))}{z}\Big) \Bigg[\underbrace{(T_o/w_o)^{\theta} \tau_{os}^{-\theta}}_{\text{Channel 2}} + \underbrace{(T_s/w_s)^{\theta} (d_{os}(\varphi(z)))^{-\theta}}_{\text{Channel 3(a)}} + \\
& \qquad \underbrace{\sum_{\substack{s' \in S_o(\varphi(z), z) \\ s' \neq s, s' \neq o}} (T_{s'}/w_{s'})^{\theta} (d_{os'}(\varphi(z)) \tau_{s's})^{-\theta}}_{\text{Channel 4}} \Bigg]^{-\frac{1-\sigma}{\theta}} d\mu_o(z) \\
& + \sum_{o \neq s} \int_Z \mathbb{1}[s \notin S_o(\varphi(z), z)] \Big(\frac{h(\varphi(z))}{z}\Big) \Bigg[\underbrace{(T_o/w_o)^{\theta} \tau_{os}^{-\theta}}_{\text{Channel 2}} + \underbrace{\sum_{\substack{s' \in S_o(\varphi(z), z) \\ s' \neq s, s' \neq o}} (T_{s'}/w_{s'})^{\theta} (d_{os'}(\varphi(z)) \tau_{s's})^{-\theta}}_{\text{Channel 4}} \Bigg]^{-\frac{1-\sigma}{\theta}} d\mu_o(z) \Bigg\}^{\frac{1}{1-\sigma}}
\end{aligned}
\tag{39}
$$

The first line summarizes the prices charged by local firms that operate only in location s, i.e., local single-unit firms. Following an ICT cost reduction, these firms contribute to local efficiency improvement by increasing effective productivity $z/h(\varphi(z))$ (channel 1). The second line shows that in addition to the local production channel (channel 1), local multi-unit firms can reduce their costs of communication with their nonheadquarters establishments, expand to more locations, and enhance local efficiency through third-location trade (channel 4). The third and fourth lines summarize the prices charged by outside firms with establishments in location s. Their headquarters' production affects local efficiency in s through the traditional trade channel (channel 2). Moreover, their local establishments benefit from productivity improvements and the reduction in the cost of communicating with headquarters, which directly raises local efficiency in location s (channel 3(a)). As firms reorganize their geographic coverage, these firms also affect local efficiency through entry and exit (channel 3(b)). Additionally, nonheadquarters establishments of outside firms affect local efficiency through third-location trade (channel 4). The last line shows that outside firms that do not have a local establishment still affect local efficiency through the traditional and third-location trade channels.

Below is a summary of the different channels through which local efficiency is affected.

- Channel 1: Local production by local firms
- Channel 2: Traditional trade by outside firms' headquarters production
- Channel 3: Multi-unit production:
  (a) : Local production by outside firms
  (b) : Entry and exit of outside firms
- Channel 4: Third-location trade by firms' nonheadquarters production

Rich interaction between firms' ICT adoption and multi-unit production facilitates the wide spread of efficiency gains from ICT enhancement. Particularly, multi-unit firms act as an important channel through which benefits from ICT improvement spread across locations—both through their existing establishments and through endogenous entry and exit when they reoptimize their geographic footprints.

C Estimation Appendix

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

Since the production function is constant return to scales with labor as the only input and firms compete monopolistically, the establishment's wages are proportional to its sales with a factor of $(\sigma - 1)/\sigma$. Combining this with the establishment sales in Equation (27), we can obtain the wage bills at establishment $s \in S$ as:

$$\begin{aligned} w_s L_{os}(S,\varphi) &= \frac{\sigma-1}{\sigma}\text{sales}_{os}(S,\varphi) = \frac{\sigma-1}{\sigma}\sum_k \text{sales}_{ok\leftarrow s}(S,\varphi) \\ &= \frac{(\sigma-1)^{\sigma}}{\sigma^{\sigma}}\tilde{\Gamma}\left(\frac{z}{h(\varphi)}\right)^{\sigma-1}\left(\frac{T_s}{w_s}\right)^{\theta} d_{os}(\varphi)^{-\theta}\sum_k E_k P_k^{\sigma-1}\Phi_{ok}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}\tau_{sk}^{-\theta}, \end{aligned} \tag{40}$$

where $\Gamma\left(\frac{\theta-\sigma+1}{\theta}\right)$. Then, the employment at establishment $s \in S$ is:

$$L_{os}(S,\varphi) = \frac{(\sigma-1)^{\sigma}}{\sigma^{\sigma}}\tilde{\Gamma}\left(\frac{z}{h(\varphi)}\right)^{\sigma-1} T_s^{\theta} w_s^{-(\theta+1)} d_{os}(\varphi)^{-\theta}\sum_k E_k P_k^{\sigma-1}\Phi_{ok}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}\tau_{sk}^{-\theta}. \tag{41}$$

Similarly, the employment at the headquarters o is:

$$L_{oo}(S,\varphi) = \frac{(\sigma-1)^{\sigma}}{\sigma^{\sigma}}\tilde{\Gamma}\left(\frac{z}{h(\varphi)}\right)^{\sigma-1} T_o^{\theta} w_o^{-(\theta+1)}\sum_k E_k P_k^{\sigma-1}\Phi_{ok}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}\tau_{ok}^{-\theta}, \tag{42}$$

where we take into account that there is no location-pair communication cost at the headquarters.

Therefore, we can derive the logarithm of the employment share at nonestablishment locations $s \in S, s \neq o$, normalized by the logarithm of the headquarters employment share, as:

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

where $\omega_{ok}(S,\varphi) \equiv \frac{E_k P_k^{\sigma-1}\Phi_{ok}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}}{\sum_{k'} E_{k'} P_{k'}^{\sigma-1}\Phi_{ok'}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}}$.

Given the parameterization of $d_{os}(\varphi) = e^{\beta^d(\varphi)\log\text{Miles}_{os}}$, we can write the above equation as

$$\log\tilde{\zeta}_{os}(S,\varphi) = -\theta\beta^d(\varphi)\log\text{Miles}_{os} + \log\left(\frac{\sum\omega_{ok}(S,\varphi)\tau_{sk}^{-\theta}}{\sum\omega_{ok}(S,\varphi)\tau_{ok}^{-\theta}}\right) + \theta\log(T_s/T_o) - (\theta+1)\log(w_s/w_o). \tag{43}$$

Note that this equation is of the same form as the within-firm sales distribution in Equation (14), except for the coefficient on the relative wages term $\log(w_s/w_o)$.

C.2 National Science Foundation Network

This appendix section provides a brief history of 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, 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).[69] Moreover, NSFNET provided connections to the backbone nodes from regional networks; these regional networks were in turn connected to smaller regional and campus networks.

From 1990, NSFNET saw its second round of upgrades and expansion. By the end of 1991, the network had added three more nodes: 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 MCI's junction places to ensure robust infrastructure and stable power.

1991–1995: Commercialization and Privatization

The goal of 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.

In March 1991, the *Acceptable Use Policy* was revised to allow 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."[70] 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.[71]

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[69] The NSF partnered with 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.

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

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

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 A.3, adapted from Table 5.1 in Greenstein (2015), shows the number of Internet service providers listed in *Boardwatch Magazine* during 1993–1998.[72] 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

NSFNET was closely related to its predecessor, ARPANET, funded by the Department of Defense since the 1960s. Following ARPANET, NSFNET used packet-switching technology and the TCP/IP protocol.[73] The node locations of NSFNET were also influenced by 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.

C.3 Reduced Form Evidence: Robustness and Additional Results

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

C.3.1 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,

$$\text{HQDistToNode}_i \mid X_i \sim \log N(X_i\beta, \sigma^2). \tag{44}$$

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[72] *Boardwatch Magazine* was initially a journal for bulletin board systems. From the late 1990s, it became a magazine for the Internet service providers.

[73] 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 the Internet Protocol (IP) ensure that these packets reach the target device and are reassembled in the right order.

The covariates X_i are comprised 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 local population, logarithm of median household income, share of 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

$$\begin{aligned} & f_{\mathrm{D}|X}(\mathrm{HQDistToNode}_i \mid X_i) \\ & \quad = \frac{1}{\mathrm{HQDistToNode}_i \sqrt{2\pi\sigma^2}} \exp\left(-\frac{(\log \mathrm{HQDistToNode}_i - X_i\beta)^2}{2\sigma^2}\right). \end{aligned} \tag{45}$$

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 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, $\mathrm{HQDistToNode}_i \sim \log N(\overline{\mu}, \overline{\sigma})$. Therefore, the weight is given by

$$w_i = \frac{\sigma}{\overline{\sigma}} \exp\left(\frac{(\log \mathrm{HQDistToNode}_i - X_i\beta)^2}{2\sigma^2} - \frac{(\log \mathrm{HQDistToNode}_i - \overline{\mu}))^2}{2\overline{\sigma}^2}\right). \tag{46}$$

I use observations at the beginning of the sample period in 1987 to estimate the parameters $(\beta,\ \sigma,\ \overline{\mu},\ \overline{\sigma})$ via the maximum likelihood estimator. To show that the distance measure is not correlated with firm and location characteristics before the privatization, I regress the distance on those covariates using the 1987 observations and adjust the regression by the weights specified in Equation (46):

$$\mathrm{HQDistToNode}_i = \alpha + X_i\beta + \alpha_i^{\mathrm{Industry}} + \alpha_i^{\mathrm{State}} + u_i. \tag{47}$$

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 A.4 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.

C.3.2 Excluding University Towns

Given that many NSFNET nodes were located in university towns, one may concern 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 in 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 A.13 shows that the coefficient is estimated at 0.4 and is statistically significant at 1% level. This result reassures that proximity to universities is not driving my baseline result.

C.3.3 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 A.14 reports the difference-in-differences estimates of the effect of the Internet privatization on firms' employment, employment per establishment, and wage rate. In line with the estimates for geographic expansion, the estimate for firm total employment is negative and statistically significant at the 10% level, indicating that the privatization increased firms' overall size. However, the privatization did not have significant effects on establishment size or wages.

C.3.4 Location of New Establishments

I test whether firms close to nodes are more likely to set up establishments also 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 A.15, 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 A.15 show the results with the average county characteristics of new establishments as dependent variables. For instance, column (2) shows that firms headquartered closer to nodes tend to set up establishments in counties with larger populations, but 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.

C.4 Third-Step: Solving Firm Location Choice Problem

This appendix section demonstrates that the single crossing differences condition in Arkolakis et al. (2021) applies to my particular settings and provides a brief explanation of the computation algorithm.

Single crossing differences condition. Let the firm's headquarter location o, productivity z, and the 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

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

The goal is to show that a sufficient condition for the single crossing differences condition holds: the marginal benefit $D\pi_o(s;S,\varphi,z)$ decreases monotonically as S increases. Let $S_1\subseteq S_2$ be given and location, and neither includes location s. We want to show that $D\pi_o(s;S_1,\varphi,z)\geq D\pi_o(s;S_2,\varphi,z)$.

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,

$$\begin{aligned}D\pi_o(s;S_1,\varphi,z)-D\pi_o(s;S_2,\varphi,z)&=\frac{\sigma^{-\sigma}}{(\sigma-1)^{1-\sigma}}\tilde{\Gamma}\left(\frac{z}{h(\varphi)}\right)^{\sigma-1}\sum_k E_k P_k^{\sigma-1}\times\\&\left[\Phi_{ok}(S_1\cup\{s\},\varphi)^{\frac{\sigma-1}{\theta}}-\Phi_{ok}(S_1,\varphi)^{\frac{\sigma-1}{\theta}}-\Phi_{ok}(S_2\cup\{s\},\varphi)^{\frac{\sigma-1}{\theta}}+\Phi_{ok}(S_2,\varphi)^{\frac{\sigma-1}{\theta}}\right]\geq 0.\end{aligned}$$

A sufficient condition for the above inequality to hold is that, for each market k,

$$(\Phi_{ok}(S_1\cup\{s\},\varphi)^{\frac{\sigma-1}{\theta}}-\Phi_{ok}(S_1,\varphi)^{\frac{\sigma-1}{\theta}})-(\Phi_{ok}(S_2\cup\{s\},\varphi)^{\frac{\sigma-1}{\theta}}-\Phi_{ok}(S_2,\varphi)^{\frac{\sigma-1}{\theta}})\geq 0.$$

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 only keep S for brevity. We would like to show $\Delta f(S_1)\geq\Delta f(S_2)$ 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 $\frac{\sigma-1}{\theta}-1$. For example, if $\frac{\sigma-1}{\theta}-1=0$, the additional benefit $\Delta f(S_1)=\Delta f(S_2)=T_s^\theta/(w_s d_{os}(\varphi)\tau_{sk})^{-\theta}$ is independent of the firm's other locations.

In my setting, where $\frac{\sigma-1}{\theta}-1<0$, $f(S)$ is concave. Thus, $\Delta f(S_1)\geq\Delta f(S_2)$ where $S_1\subseteq S_2$; that is, the benefit of an additional location s decreases as the firm has more establishments in other locations. Therefore, the single crossing differences condition holds.

This observation is critical to the computation algorithm. In particular, the smallest benefit of an establishment in location s is when the firm already has establishments in all other locations, whereas the biggest benefit is when the firm has no other establishments. If the smallest benefit is positive, location s must be included in the optimal set. Conversely, if the biggest benefit is negative, location s should not be in the optimal set.

Computation algorithm. The algorithm below is reminiscent of the single-agent squeezing procedure described in Arkolakis et al. (2021). For the sake of brevity, 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 headquarter 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. Repeat this procedure until $\tilde{S}$ converges to a fixed point.
3. If $\tilde{S}$ converges to a singleton, 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 evaluate the profit at local optima to obtain the global optimum.

D Policy Simulation Appendix

This appendix section provides details on the decomposition of efficiency gains, by decomposing local price indices, and presents the decomposition results in the policy simulation of the Internet privatization and the local ICT cost reduction.

D.1 Decomposing Local Efficiency Gains

Denote the firm by i and the firm headquarters location by o. In each market k, the ideal price index is defined by $P_k = \left(\sum_{o=1}^{N} \int_0^{m_o} p_{ok}(i)^{1-\sigma} di\right)^{\frac{1}{1-\sigma}}$, where m_o is the exogenous mass of firms headquartered in location o and $p_{ok}(i)$ is the firm-specific price charged in market k by the firm. Depending on whether a firm is headquartered in location k (i.e., local firms versus outside firms) and whether a firm sets up an establishment in location k in the benchmark or counterfactual equilibrium, we can decompose the price index into the contributions from five types of firms:

$$P_k^{1-\sigma} = (P_k^{\text{local}})^{1-\sigma} + (P_k^{\text{out},11})^{1-\sigma} + (P_k^{\text{out},10})^{1-\sigma} + (P_k^{\text{out},01})^{1-\sigma} + (P_k^{\text{out},00})^{1-\sigma},$$

where P_k^{local} is the price index of *local firms*, $P_k^{\text{out},11}$ is the price index of outside firms that set up establishments in location k in both the benchmark and counterfactual equilibria (i.e., *stayers*), $P_k^{\text{out},10}$ is the price index of outside firms that set up establishments in the location in the benchmark equilibrium but exit in the counterfactual equilibrium (i.e., *exiters*), $P_k^{\text{out},01}$ is the price index of outside firms that do not set up establishments in the location in the benchmark equilibrium but enter the location in the counterfactual equilibrium (i.e., *entrants*), and $P_k^{\text{out},00}$ is the price index of outside firms that do not set up establishments in the location in either the benchmark or the counterfactual equilibrium (i.e., *never-comers*). Specifically, these price indices are defined as follows. Let $S^0(i)$ and $S^1(i)$ be the set of establishment locations of firm i in the benchmark equilibrium and counterfactual equilibrium, respectively. Then, we can express the price index of each type of firm by:

$$\begin{aligned}
P_k^{\text{local}} &= \left(\int_0^{m_k} p_{kk}(i)^{1-\sigma} di\right)^{\frac{1}{1-\sigma}} \\
P_k^{\text{out},11} &= \left(\sum_{o \neq k} \int_0^{m_o} \mathbb{1}[k \in S^0(i), k \in S^1(i)]\, p_{ok}(i)^{1-\sigma} di\right)^{\frac{1}{1-\sigma}} \\
P_k^{\text{out},10} &= \left(\sum_{o \neq k} \int_0^{m_o} \mathbb{1}[k \in S^0(i), k \notin S^1(i)]\, p_{ok}(i)^{1-\sigma} di\right)^{\frac{1}{1-\sigma}} \\
P_k^{\text{out},01} &= \left(\sum_{o \neq k} \int_0^{m_o} \mathbb{1}[k \notin S^0(i), k \in S^1(i)]\, p_{ok}(i)^{1-\sigma} di\right)^{\frac{1}{1-\sigma}} \\
P_k^{\text{out},00} &= \left(\sum_{o \neq k} \int_0^{m_o} \mathbb{1}[k \notin S^0(i), k \notin S^1(i)]\, p_{ok}(i)^{1-\sigma} di\right)^{\frac{1}{1-\sigma}}.
\end{aligned}$$

Let P_k denote the price index in location k in the benchmark equilibrium and $\tilde{P}_k$ the price index in the counterfactual equilibrium. As efficiency gains are captured by changes in the inverse of the price index, we can thus decompose the changes in efficiency as follows:

$$
\begin{aligned}
&\log \tilde{W}_k - \log W_k = \log 1/\tilde{P}_k - \log 1/P_k = \log P_k - \log \tilde{P}_k \\
&= \frac{1}{1-\sigma}\Big[\log\big((P_k^{\text{local}})^{1-\sigma} + (P_k^{\text{out},11})^{1-\sigma} + (P_k^{\text{out},10})^{1-\sigma} + (P_k^{\text{out},01})^{1-\sigma} + (P_k^{\text{out},00})^{1-\sigma}\big) - \\
&\qquad \log\Big((\tilde{P}_k^{\text{local}})^{1-\sigma} + (\tilde{P}_k^{\text{out},11})^{1-\sigma} + (\tilde{P}_k^{\text{out},10})^{1-\sigma} + (\tilde{P}_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\Big) \Big] \\
&= \frac{1}{1-\sigma}\Big[\log\big((P_k^{\text{local}})^{1-\sigma} + (P_k^{\text{out},11})^{1-\sigma} + (P_k^{\text{out},10})^{1-\sigma} + (P_k^{\text{out},01})^{1-\sigma} + (P_k^{\text{out},00})^{1-\sigma}\big) - \\
&\qquad \log\Big((P_k^{\text{local}})^{1-\sigma} + (P_k^{\text{out},11})^{1-\sigma} + (P_k^{\text{out},10})^{1-\sigma} + (P_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\Big) + \\
&\qquad \log\Big((P_k^{\text{local}})^{1-\sigma} + (P_k^{\text{out},11})^{1-\sigma} + (P_k^{\text{out},10})^{1-\sigma} + (P_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\Big) - \\
&\qquad \log\Big((P_k^{\text{local}})^{1-\sigma} + (P_k^{\text{out},11})^{1-\sigma} + (P_k^{\text{out},10})^{1-\sigma} + (\tilde{P}_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\Big) + \\
&\qquad \log\Big((P_k^{\text{local}})^{1-\sigma} + (P_k^{\text{out},11})^{1-\sigma} + (P_k^{\text{out},10})^{1-\sigma} + (\tilde{P}_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\Big) - \\
&\qquad \log\Big((P_k^{\text{local}})^{1-\sigma} + (P_k^{\text{out},11})^{1-\sigma} + (\tilde{P}_k^{\text{out},10})^{1-\sigma} + (\tilde{P}_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\Big) + \\
&\qquad \log\Big((P_k^{\text{local}})^{1-\sigma} + (P_k^{\text{out},11})^{1-\sigma} + (\tilde{P}_k^{\text{out},10})^{1-\sigma} + (\tilde{P}_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\Big) - \\
&\qquad \log\Big((P_k^{\text{local}})^{1-\sigma} + (\tilde{P}_k^{\text{out},11})^{1-\sigma} + (\tilde{P}_k^{\text{out},10})^{1-\sigma} + (\tilde{P}_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\Big) + \\
&\qquad \log\Big((P_k^{\text{local}})^{1-\sigma} + (\tilde{P}_k^{\text{out},11})^{1-\sigma} + (\tilde{P}_k^{\text{out},10})^{1-\sigma} + (\tilde{P}_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\Big) - \\
&\qquad \log\Big((\tilde{P}_k^{\text{local}})^{1-\sigma} + (\tilde{P}_k^{\text{out},11})^{1-\sigma} + (\tilde{P}_k^{\text{out},10})^{1-\sigma} + (\tilde{P}_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\Big) \Big] \\
&\equiv \Big(\Delta^{\text{out},00} + \Delta^{\text{out},01} + \Delta^{\text{out},10} + \Delta^{\text{out},11} + \Delta^{\text{local}}\Big),
\end{aligned}
$$

where Δ^{local}, $\Delta^{\text{out},11}$, $\Delta^{\text{out},10}$, $\Delta^{\text{out},01}$, and $\Delta^{\text{out},00}$ represent the contributions to the changes in the price index from the different types of firms.

I apply this decomposition to the three policy simulations.

Internet privatization. Table A.18 breaks down the efficiency gain in each census division into the 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 17% and 53%, respectively, while exiters reduce local efficiency by 7% due to higher shipping costs. Those outside firms that have never set up local establishments account for approximately 20% of the changes through trade—both the traditional trade channel from their headquarters and the third-location trade channel from their nonheadquarters establishments. In sum, outside firms account for more than four-fifths of the local efficiency gains. Local firms, in contrast, account for less than 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 60% of the local efficiency gains, underscoring the importance of multi-unit production across locations in determining local efficiency gains.

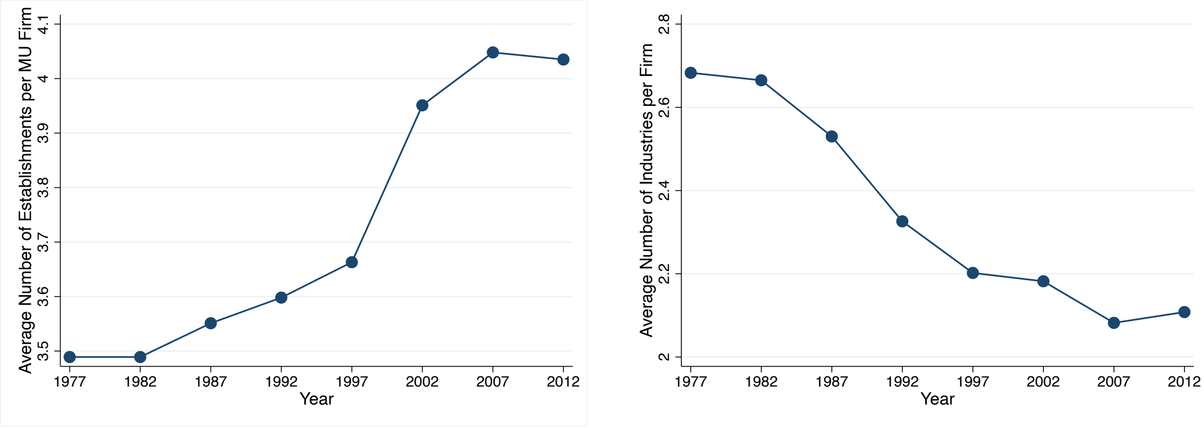
Local ICT cost reduction. Table A.19 shows how a local ICT cost reduction in the West South Central census division is transmitted to other locations. The efficiency gains in the West South Central are primarily driven by the productivity increases of local firms, as the fixed costs of ICT adoption decrease. In other locations, however, efficiency gains are driven by outside firms. On average, stayers contribute 37% 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 the 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. Meanwhile, 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, of approximately -4% on average, on other locations' efficiency. Never-comers contribute 25% of the efficiency changes, driven by spillover through trade.

The lower panel of Table A.19 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 A.20 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 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 approximately 70% of the efficiency gains on average.

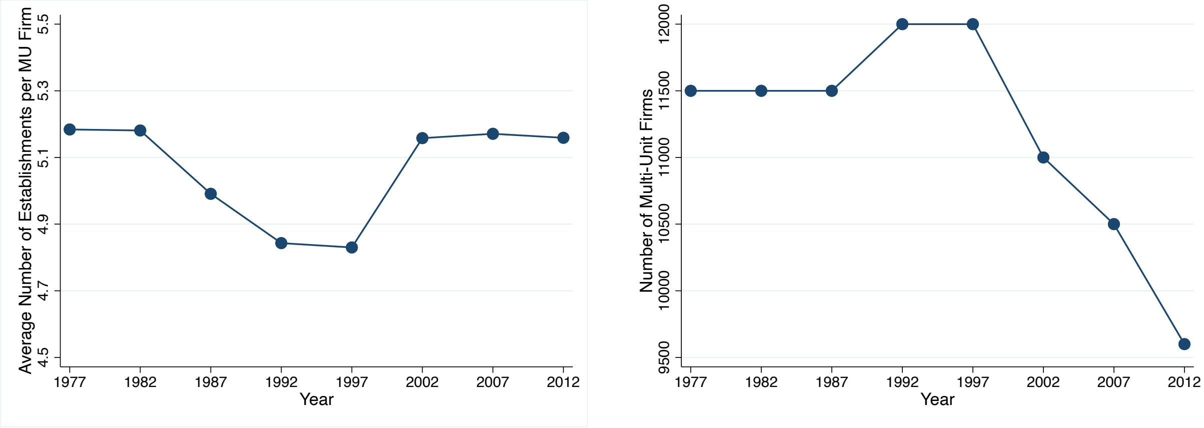
Additional Figures

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



A. #Establishments per FIRMID–Industry

B. #Industries per FIRMID

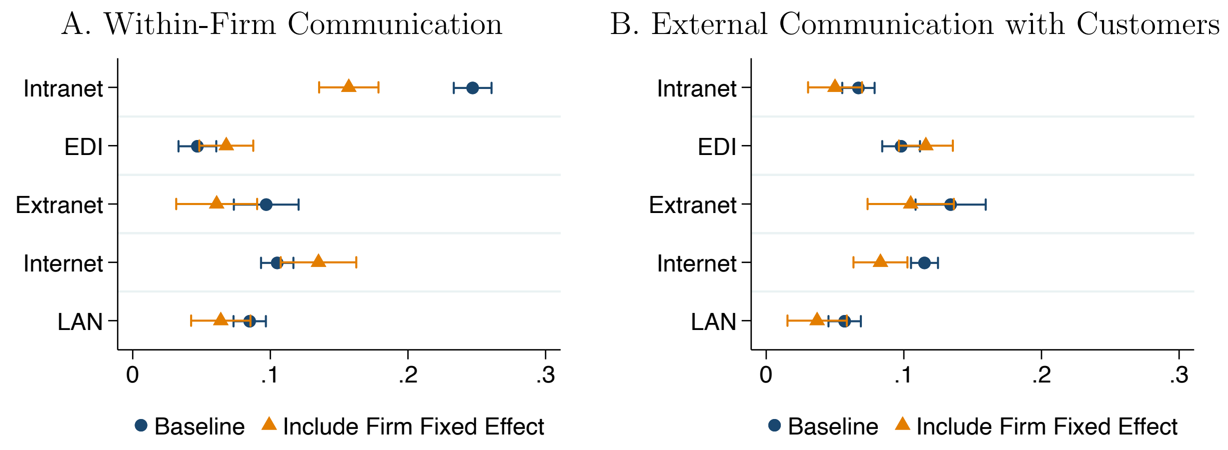


C. #Establishments per FIRMID

D. #Multi-Unit Firms

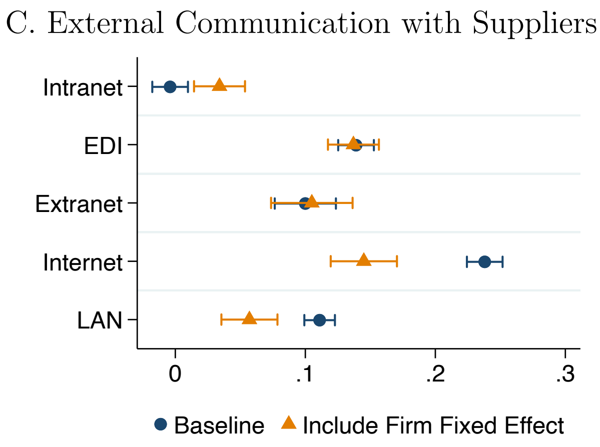
Notes: These figures show the span of control for multi-unit firms in the manufacturing sector from the Longitudinal Business Database (LBD). Panel A plots the average number of establishments per firm, where each firm is a FIRMID×six-digit NAICS industry pair. Panel B–D define firm by the FIRMID. Panel 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 A.2: **Establishments' ICT Adoption and Communication**



A. Within-Firm Communication

B. External Communication with Customers



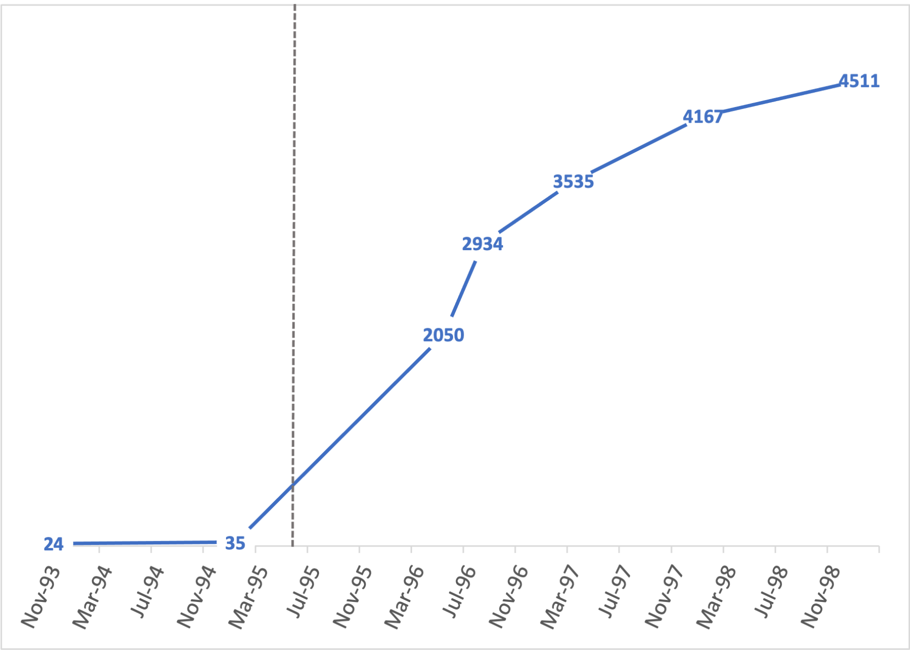
C. External Communication with Suppliers

Notes: These figures use establishment-level data from the Computer Network Use Supplement (CNUS) and plot the coefficients of a regression of the form:

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

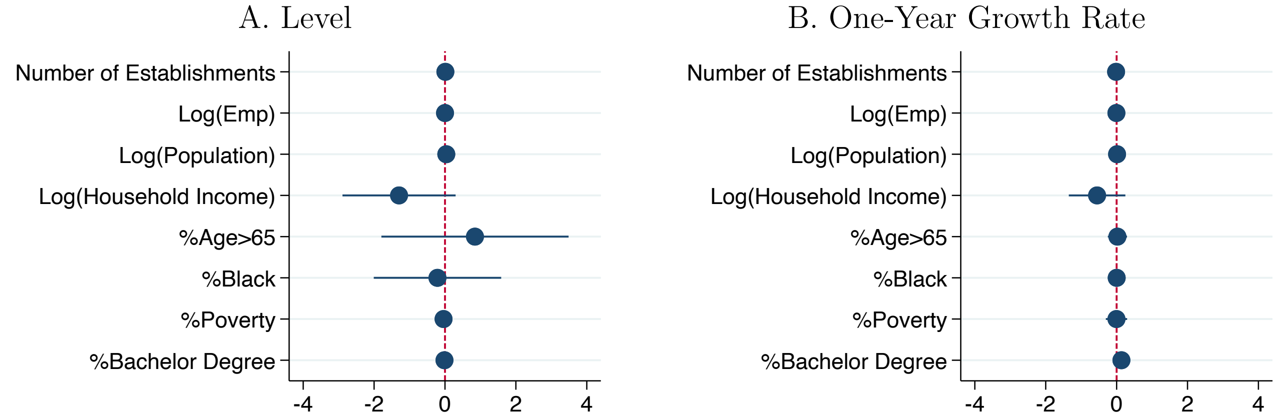
where the dependent variables are indicators set to one if an establishment i provides information to other company units (Panel A), external customers (Panel B), and external suppliers (Panel C), respectively. The independent variables include indicators set to one if establishment i adopted Intranet, 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 employment, the 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. Circle markers correspond to this baseline regression. Triangle markets correspond to regressions that further include firm fixed effect. Confidence intervals are at the 95% level.

Figure A.3: Number of Internet Service Providers (ISPs) Listed in *Boardwatch Magazine*



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

Figure A.4: **Regression Estimates of Distance to the Nearest NSFNET Node on Firm and County Characteristics**


A. Level

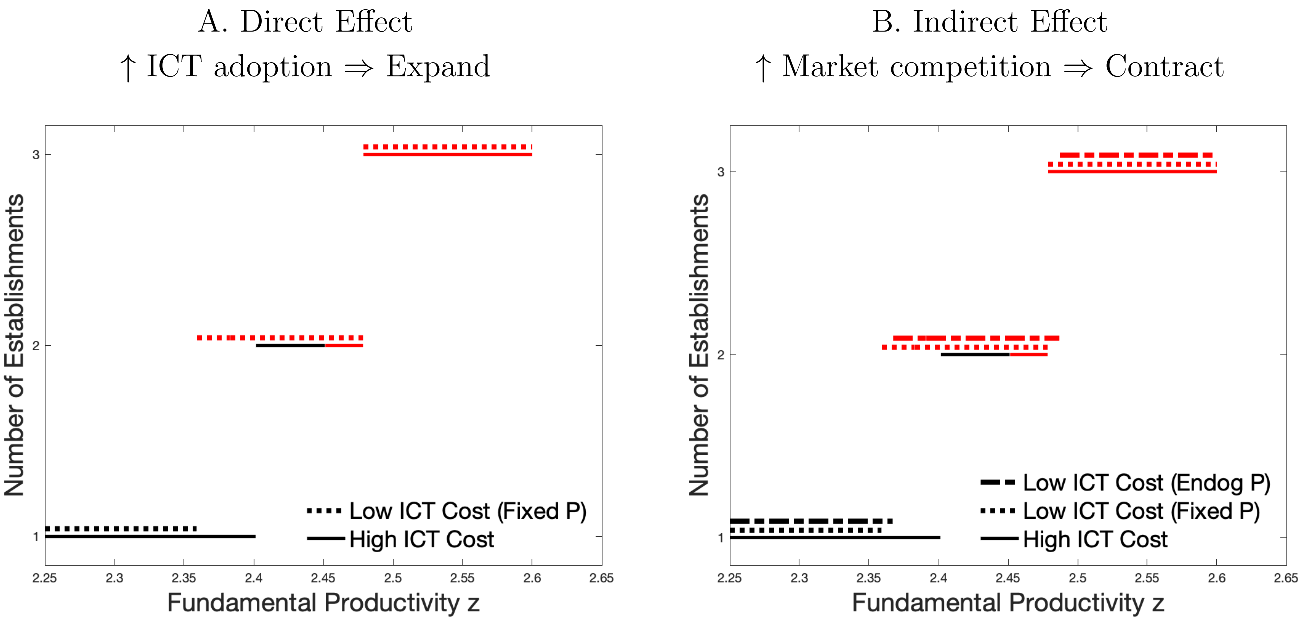
B. One-Year Growth Rate

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 local population, logarithm of median household income, share of the population below the poverty line, share of 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 A.5: **Equilibrium Effects of an ICT Cost Reduction**


A. Direct Effect

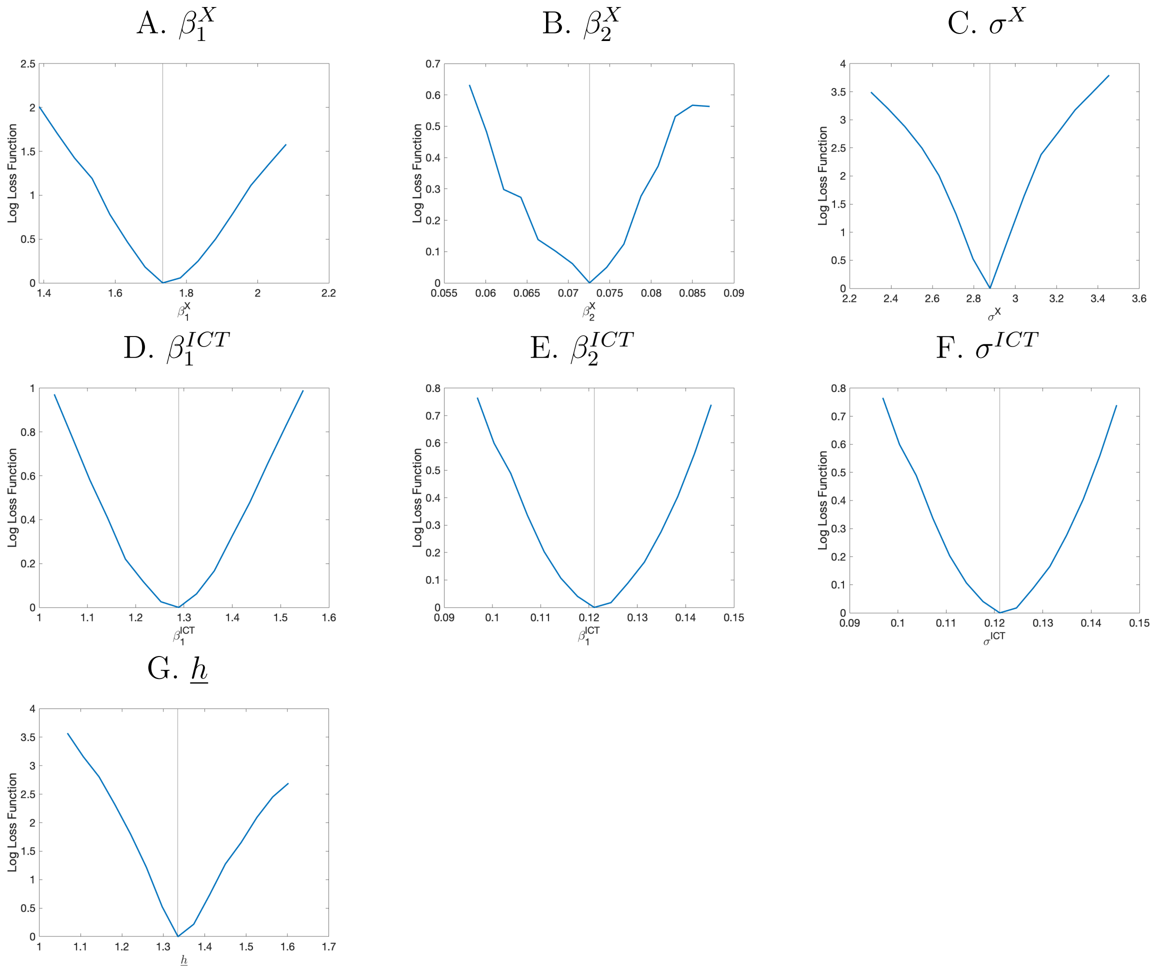
↑ ICT adoption ⇒ Expand

B. Indirect Effect

↑ Market competition ⇒ 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 A.6: **Loss Function from Structural Estimation**



A. β_1^X B. β_2^X C. σ^X

D. β_1^{ICT} E. β_2^{ICT} F. σ^{ICT}

G. $\underline{h}$

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.8: **Establishment Summary Statistics of the 1999 Computer Network Use Supplement**

	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 set to one if the establishment is connected to a type of network. Variables regarding communication are indicators set to one if the establishment communicates with other company units, external customers, and external suppliers, respectively.

Table A.9: **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 set to one if a firm has more than one establishment.

Table A.10: **Firms' ICT Adoption, Geographic Expansion, and Communication Patterns**

	Growth Rate from 1997 to 2002 in Number of Establishments (1)	Communication Within-Firm (2)	Communication Customer (3)	Communication Supplier (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 estimate 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, and 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 A.11: **Robustness Check of Firms' ICT Adoption and Expansion**

Dep. Var: Growth Rate during 1997–2002 in	FIRMID–Industry: #Establishments in Mfg. Sector: Baseline (1)	FIRMID–Industry: #Establishments in Mfg. Sector: Single-Industry Firms (2)	FIRMID: #Establishments in All Sectors (3)	FIRMID: Employment in All Sectors (4)	FIRMID: %Employment 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, and 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 that firm i has, where firm is defined by the FIRMID–six-digit NAICS pair. Column (2) restricts 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) and (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 A.12: **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 firm fixed effect. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A.13: **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 A.14: **Estimates of the Effect of ICT on Firms' Expansion: Intensive Margin**

	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, logarithm of employment per establishment, and logarithm of average wage rate of the firm, respectively, for 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 A.15: **Estimates of the Effect of ICT on Firms' Expansion: Location of New Establishments**

	$\overline{\text{DistToNode}}^{\text{New}}$ (1)	$\overline{\text{Log(Pop)}}^{\text{New}}$ (2)	$\overline{\text{Log(HH Income)}}^{\text{New}}$ (3)	$\overline{\text{\%Poverty}}^{\text{New}}$ (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

	$\overline{\text{\%Black}}^{\text{New}}$ (5)	$\overline{\text{\%Age>65}}^{\text{New}}$ (6)	$\overline{\text{\%Bachelor's Degree}}^{\text{New}}$ (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 variable for columns (2)–(7) is 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, 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 A.16: **Estimates of Census Division Fixed Effects and the State of Technology in 1999**

	Census Division Fixed Effect		State of Technology
	Raw Estimates (1)	Purified Estimates (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 A.17: **Average Fixed Costs of Setting Up Establishments and Adopting ICT**

Census Division	Average Fixed Costs (in Millions USD) Setting Up Establishments (Establishment Location)	 Adopting ICT (Headquarters Location)
New England	2.89	1.35
Middle Atlantic	3.11	1.45
East North Central	2.86	1.44
West North Central	2.37	1.30
South Atlantic	4.57	1.44
East South Central	3.24	1.37
West South Central	3.40	1.35
Mountain	2.77	1.19
Pacific	3.51	1.16

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 A.18: **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	1.23	17	53	-7	21	17
Middle Atlantic	1.04	13	34	-4	34	23
East North Central	1.41	19	39	-5	4	43
West North Central	1.36	49	22	-3	16	15
South Atlantic	1.35	64	17	-12	5	25
East South Central	1.42	58	24	-6	14	10
West South Central	0.93	33	24	-7	35	14
Mountain	1.41	58	26	-8	14	9
Pacific	1.47	31	56	-6	3	16
National Average	1.29	38	33	-6	16	19

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 D.1. Column (6) reports the contribution from local firms that are headquartered in each location.

Table A.19: **Decomposing Efficiency Gains: Local ICT Cost Reduction**

Census Division	%Change in efficiency	Decomposition (%)				
		Outside Firms				Local Firms
	(1)	Stayers (2)	Entrants (3)	Exiters (4)	Never-Comers (5)	(6)
West South Central	0.023	-1	0	-28	0	128
Other Census Divisions	0.011	37	47	-4	21	0
New England	0.009	0	64	0	36	0
Middle Atlantic	0.011	23	64	-5	18	0
East North Central	0.008	81	13	-9	17	1
West North Central	0.013	46	39	0	17	1
South Atlantic	0.009	18	61	-2	24	0
East South Central	0.013	35	53	-8	20	0
Mountain	0.012	29	43	-3	31	0
Pacific	0.013	62	36	-4	5	0

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 D.1. Column (6) reports the contribution from local firms that are headquartered in each location.

Table A.20: **Decomposing of Efficiency Gains: National ICT Cost Reduction**

	%Change in Efficiency	Decomposition (%)				
		Outside Firms				Local Firms
	(1)	Stayers (2)	Entrants (3)	Exiters (4)	Never-Comers (5)	(6)
New England	0.015	10	21	0	22	46
Middle Atlantic	0.015	2	62	-4	13	27
East North Central	0.011	76	6	-7	10	15
West North Central	0.012	17	42	0	28	13
South Atlantic	0.013	10	62	-1	17	12
East South Central	0.015	26	38	-7	13	30
West South Central	0.014	49	18	-1	12	22
Mountain	0.010	1	69	-4	34	0
Pacific	0.013	80	20	-3	3	0
National Average	0.013	30	38	-3	17	18

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 D.1. Column (6) reports the contribution from local firms that are headquartered in each location.