Information and Communication Technology and Firm Geographic Expansion*

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Abstract

Information and communication technologies (ICT) can widen firms' geographic span of control by reducing internal communication costs. Combining comprehensive establishment-level datasets with ownership linkages, geographic locations, and ICT usages, I document that US manufacturers have expanded geographically over the past three decades and that firms with more advanced technologies (i.e., Intranet) have larger geographic coverages. To estimate the effects of ICT on firms' geographic span of control, I exploit a historic event in ICT developments in the United States: Internet privatization in the early 1990s. Results suggest that better access to ICT helped firms expand to more counties and that Internet privatization accounted for around 38% of the total increase in firms' geographic coverage during 1995-2007. Using a model where firms endogenously adopt advanced technologies and choose multiple production locations, I estimate that the Internet privatization reduced the manufacturing price by 1.76%. The counterfactual analysis highlights the importance of multi-unit production in evaluating the benefits of ICT improvements. Compared to a trade-only model, a model with multi-unit firms predicts that efficiency gains are larger and more geographically dispersed.

JEL Codes: D83, F12, O14, O18, O33

Keywords: Information and communication technology, firm organization, geography

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1 Introduction

Information and communication technologies (ICT) have experienced dramatic improvements over the past three decades. Governments worldwide have spent millions in infrastructure construction, paving the way for access to technology; private businesses have also made significant investments, hoping that ICT improves firm performance. Research, however, is inconclusive on whether ICT enhancements yielded large gains in economic activities. This paper studies a novel channel through which ICT affects firm decisions: geographic expansion. Concurrently with the ICT developments, firms' geographic span of control, e.g., the number of a firm's establishments, has increased over time. While anecdotes often attribute firm geographic expansion to the improvements of ICT, empirical evidence is scarce. Moreover, we have little knowledge about the gains from ICT associated with firm production at multiple locations, nor the geographic distribution of these gains.

The answers to these questions depend crucially on firms' geographic expansion and contraction decisions in response to technological enhancements. Another fact motivates the study of multi-unit firms—firms that operate in more than one establishment—is that these firms play a vital role in production in the United States. They account for the majority of employment and output in the manufacturing sector.[1] Understanding the location choices of multi-unit firms is of first-order importance.

This paper shows empirically that ICT improvements help widen firms' geographic span of control, and then proposes a model of multi-unit firms and their ICT adoption to quantify the gains from ICT improvements. I find that multi-unit production is important for evaluating the gains from ICT and government investment in communication infrastructure. In particular, multi-unit firms work as a channel for technology spillover across space. The geographic footprints of firms, in turn, is affected by the technology improvements and thus affect the distributions of gains from ICT improvements.

I establish these results in five steps. First, I leverage a comprehensive dataset with establishment-level ownership linkages and geographic locations, and augment it with establishments' ICT adoptions to document two facts. One is that firms in the US manufacturing sector have increased their geographic span of control, especially those firms with multiple production sites: the average number of counties per firm increased by 25% for multi-unit firms during 1990-2010. Using the matched sample, I also document that firms with advanced ICT software are associated with a larger geographic span of control. Identifying the effect of ICT, however, is know to be difficult, as more productive firms are more likely to

[1]Bernard and Jensen (2007) documents that multi-unit firms account for 78% of the employment and 88% of the output in the manufacturing sector using 1987–1997 Census of Manufactures.

adopt advanced technology and have a larger geographic coverage.

In the second step, I overcome this difficulty by exploiting quasi-experimental variations from a historical event in the history of US Internet development: the Internet privatization in 1995. Before the privatization, the first high-speed Internet backbone in the US was managed by the National Science Foundation (NSF) and predominantly served the research and higher education community. Commercial use was restricted. The privatization of NSFNET was completed in 1995 and transformed the Internet to the private sector, followed by drastic improvements in almost all aspects of information and communication technology. The timing of the explosive developments, however, was unexpected. As described in Greenstein (2015), it was difficult for contemporaneous observers to predict the outcomes of Internet privatization, given its unprecedented large scale, which leads to "common shrugs" in the early 1990s. "Internet gold rush" did not happen until the NSF had finished its privatization plan.[2]

I measure a firm's exposure to the Internet privatization using the distance from the firm's headquarter to the nearest node site of the NSFNET. These node locations reflected historical reasons regarding military concerns and research institutes, which were less likely to be subject to contemporary shocks. At locations closer to the Internet backbone nodes, infrastructure such as underground cables were better laid out and developed. As the construction and installation of circuits is one major cost for Internet service providers, Internet access would be cheaper for locations with better infrastructure. These locations might also benefit from thicker labor pools with ICT experiences. I use a difference-in-indifference approach to identify the effect of the Internet privatization on firms' geographic span of control. I find that the average number of counties covered by an average firm increased by 2.7%, which accounts for 38 percent of the total increase post the privatization.

Guided by these empirical findings, in the third step, the paper proposes a model of firm ICT adoption and location choices to investigate the efficiency gains from ICT improvements. In the model, firms choose a set of locations, instead of a single location, to set up establishments but are subject to communication costs among establishments. Firms can adopt advanced ICT to reduce communication costs and thus increase firm-specific effective productivity for all establishments. 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 number of establishments. In equilibrium, reducing the cost of ICT affects firms' geographic span of control through two channels. On

[2]The history of Internet commercialization in the United States, including the deployment of Internet infrastructure, is reviewed and discussed in Greenstein (2015), Greenstein (2020). Goldstein (2020) uses the expansion of NSFNET prior to its privatization to study the effect of communication cost on scientific citations.

one hand, accompanied by a reduction in the cost of ICT, the likelihood of firms adopting ICT increases, increasing the benefit of having a larger set of production sites. Through this direct channel, the cost reduction in ICT *facilitates* firms' geographic expansion. On the other hand, the markets become more competitive as a larger fraction of firms adopt ICT to improve their effective productivity. This equilibrium channel *compresses* geographic expansion. Simulations illustrate that the fraction of multi-unit firms shows a U-shape against the cost of ICT: as the ICT cost decreases, the multi-unit firms' share first declines due to the equilibrium effect and then increases as the direct effect dominates.

In the fourth step, I estimate the model using matched dataset of firm ICT adoption and geographic footprints in three stages. First, I estimate the exogenous communication costs that rise in the distance using within-firm employment shares of each establishment. Second, I decompose location-specific fixed effects to estimate the state of technology for each location. Third, I estimate the fixed costs of setting up establishments in each location and the fixed cost of adopting ICT and productivity loss without ICT via Method of Simulated Moments (MSM). I form three sets of moments regarding firms' geographic expansion patterns, ICT adoption, and the relationship between the two decisions for the estimation. The key challenge for computing firms' optimal sets of locations is the curse of dimensionality. The number of location combinations increases drastically as the number of locations rises. I address this challenge by applying a recent algorithm proposed in Arkolakis and Eckert (2017) to solve the firm's location choice problem. Estimation results show that communication costs between establishments and the headquarter increases in the distance, with an elasticity of 0.072. Adopting advanced ICT increases firms' effective productivity by 23.7%, at an average cost equivalent to 3.8% of firms' total profit.

Finally, I use the model to investigate the distribution of efficiency gains from ICT improvements. Compared to an alternative trade-only model, the gains from ICT improvements are larger when taking the multi-unit production into account. Importantly, multi-unit firms work as a channel for technology spillover across space. As a result, my model predicts that the gains from local ICT improvements are more geographically dispersed. I use the model to simulate the Internet privatization to study the efficiency gains. Through the lens of the model, I find that the East South Central census division witnessed the largest benefits while those in the Pacific saw the least. On average, the privatization reduced the manufacturing price index by 1.76%. In a policy counterfactual, I reduce the bilateral communication cost between the Pacific and West South Central divisions. The counterfactual analysis highlights the importance of interdependency of firm location choices: while firms in the two locations experience expansion, firms in the rest of the locations see contraction. Moreover, the benefits are unequal for the two locations with equal reduction in communication costs.

Governments worldwide have spent billions on ICT infrastructure construction, including programs promoting universal Internet to reduce the uneven access to the Internet. These results underscore that gains from ICT improvements differ across geographic locations, and that it is important to understand firm responses through ICT adoption and geographic organization in shaping the gains from communication infrastructure developments.

Relation to Literature

This paper studies the effects of ICT on firm organization, reviewed in Bloom, Sadun, and Van Reenen (2010), Bresnahan (2010), and Goldfarb and Tucker (2019). Closely related, Bloom, Garicano, Sadun, and Van Reenen (2014) uses firm-level data and finds a positive correlation between the firm span of control (i.e., whether a firm has multiple establishments) and advanced ICT adoption (i.e., enterprise resource planning software and Intranet). Recent papers also document that ICT facilitates vertical fragmentation of production such as outsourcing (e.g., Fort, 2017; Jiao and Tian, 2019). To the best of my knowledge, however, there is no existing evidence on the causal relationship between ICT adoption and firm geographic span of control. This paper contributes to the literature by conducting a series of quantitative analyses to fulfill this gap. The linked dataset on firm ICT utilization and geographic footprints containing geocodes of each establishment enables me to study their relationship. By exploiting plausibly exogenous variation from Internet privatization in the United States, I provide empirical evidence on the causal effects of ICT on the firm geographic span of control by reducing internal communication costs.

This paper is also related to the literature on the effects of ICT infrastructures exploiting the interactions between time variations in the arrival of technology and geographic variations in the proximity to technology (e.g., Forman, Goldfarb, and Greenstein, 2012; Akerman, Gaarder, and Mogstad, 2015; Steinwender, 2018; Juhász and Steinwender, 2018; Hjort and Poulsen, 2019). Most of the previous literature focuses on the effects on local market outcomes such as employment and firm behaviors.[3] This paper shows that, besides direct effects on local markets, ICT improvements may have distributional effects on other locations. Specifically, I highlight the role of multi-unit firms in transmitting technology across locations. I illustrate this point in a model integrating firm ICT adoption with geographic expansion. I further use the estimated model to quantify the distribution of gains of ICT availability across locations in the United States. Results show that ignoring technology spillover through multi-unit firms may lead to underestimation of the gains from ICT improvements.

[3] Notable exceptions include Steinwender (2018) who studies the effect of telegraph development in the 18th century in the United Kingdom on trade. The paper finds significant efficiency gains through the lens of a two-country trade model with information frictions.

This paper contributes to a growing literature studying the location choice of firms regarding production at multiple locations (e.g., Ramondo and Rodríguez-Clare, 2013; Tintelnot, 2017; Hu and Shi, 2019; Hsieh and Rossi-Hansberg, 2019; Oberfield, Rossi-Hansberg, Sarte, and Trachter, 2020). In particular, the paper builds and extends on Tintelnot (2017) by incorporating the endogenous communication cost through ICT adoption. The paper furthers our understanding of multi-unit production by empirically and quantitatively demonstrating endogenous ICT as an additional source of heterogeneity. A key challenge for computing the firm optimal set of production locations rise from the combinatorial choice problem, i.e., the support of choice set is at the order of 2^N where N is the number of potential production locations. While extensively studied in several other fields such as computer science, there is little attention in this problem in economics, except small literature explicitly studying the combinatorial choice problem—examples include Jia (2008), Antras, Fort, and Tintelnot (2017) and the papers mentioned above. The paper contributes to this literature by applying the algorithm proposed in Arkolakis and Eckert (2017) to solve the firm location choice problem, and by integrating this algorithm into the estimation procedure as well as counterfactual exercises.

Outline of the paper

The rest of the paper is organized as follows. Section 1 describes the datasets. Section 2 discusses the 1995 Internet privatization and the reduced-form analysis. Section 3 develops the model, followed by structural estimation in Section 4. Section 5 conducts counterfactuals, and Section 6 concludes.

2 Data and Stylized Facts

2.1 Data

The main dataset comes from the manufacturing package of the National Establishment Time Series (NETS) Database from 1990 to 2010, a longitudinal database that covers a comprehensive set of establishments in the manufacturing sector in the US. The data is maintained by Wall & Associates and constructed from *Duns Marketing Information* (DMI) by Dun and Bradstreet (D&B). Each establishment refers to a particular line of business at a location. The data provides detailed geographic information of each establishment such as zip code, county and detailed address. Importantly, each establishment is assigned a unique D-U-N-S Number and is linked to its domestic headquarter.[4] The comprehensive geographic

[4]The headquarter identified in the NETS is called domestic ultimate headquarter, or ultimate parent firm. A firm is called a parent firm if it owns over 50% share of another firm where the other firm is called

footprints and firm ownership linkages form the basis for empirical analysis.

Firms are defined at the firm identifier (HQDUNS) $\times$ 4-digit SIC code level. This definition allows me to focus on firm expansion along the geographic dimension, instead of changes in industry compositions. When constructing measures of firm geographic span of control, I consolidate the establishments of a firm located in the same county, and restrict to those counties with at least ten employees, so as to avoid spurious reporting (see Barnatchez, Crane, and Decker, 2017).[5] The term of "establishment" and "county" are used interchangeably. For instance, as a major measure of firm geographic span of control, the number of establishments a firm operates refers to the number of counties that we see the presence of a firm. Finally, I restrict geography to the contiguous states; Alaska, Hawaii, Pueto Rico and Virgin Islands are excluded.

Panel A in Table 1 reports the firm-level summary statistics for the baseline sample. Around 6% of firms have production in multiple counties, with an average number of 1.17 counties. An average firm hires around 100 employees, while the median is 25. I do not report summary statistics for sales due to data quality concern; the imputation rate for sales is over 70%. Having this caveat in mind, the average sales is 14.3 million USD with a large variance. Column (6)–(10) further shows summary statistics for multi-unit firms.

I augment NETS with ICT information from the 2002 Harte Hanks Computer Intelligence database (HH hereafter). Similar to NETS, HH database is collected by Harte Hanks, a marketing firm, about the IT usage of establishments to sell to other firms for the marketing purpose. So the company has strong incentives to keep the datasets high quality. HH database is widely used in the literature that studies the role of information and communication technologies (e.g., Forman, Goldfarb, and Greenstein, 2012; McElheran, 2014; Bloom, Garicano, Sadun, and Van Reenen, 2014). I merge HH database with NETS for year 2002 by company name and address. The overall matching quality is satisfactory: 83.17% of manufacturing establishments in the 2002 HH database are matched with the NETS manufacturing package. Among non-manufacturing establishments from the HH database, 37.51% of them are matched in the manufacturing package of the NETS. Appendix section A.1 provides more details on the matching procedure. In addition, I use a firm's adoption of Intranet to measure the firm's internal communication cost (e.g., Forman and Zeebroeck, 2012; Bloom,

a subsidiary. A firm can be both a parent firm and a subsidiary at the same time. The ultimate parent firm is the highest level reporting unit in the family tree within the US. For instance, CEMEX Inc. is the ultimate parent firm for all establishments belonging to both CEMEX Inc. and its subsidiaries such as Cemex Materials LLC.

[5]By comparing the NETS to official data sources such as County Business Patterns (CBP) and Quarterly Census of Employment and Wages (QCEW),Barnatchez et al. (2017) finds that the NETS is able to match official data well after applying certain sample restrictions. This paper largely follows their recommendations to construct a representative sample.

Garicano, Sadun, and Van Reenen, 2014). Installation of Intranet largely facilitates the communication within a firm, making it easier to share information between the headquarter and establishments, or worker and managers, and to hold phone meetings once intranet is installed. The Harte-Hanks records whether an establishment has installed Intranet; I aggregate the Intranet adoption to the firm level, assuming that a firm has adopted Intranet as long as any of its establishment is connected via Intranet.

Panel B in Table 1 reports the summary statistics for the matched sample. Compared to the 6% multi-unit firms in the baseline sample, one-fourth of firms in the matched sample are multi-unit. Nevertheless, Column (6)–(10) show that the multi-unit firms in the matched sample are broadly comparable to those in the baseline sample. As for ICT usage, the adoption rate of Internet is high: 88% of all firms in the matched sample were connected to the Internet in 2002, which is consistent with high Internet penetration rate documented in literature (see Forman, Goldfarb, and Greenstein, 2002). Adoption rate of Intranet, on the other hand, is relatively low: Less than half of the firms installed Intranet. The adoption rate is larger for multi-unit firms at 55%. In the rest of the paper, I focus on firm's adoption of Intranet as a proxy for the firm's internal communication cost, and show that it increases firm geographic span of control.

Table 1: Summary Statistics

	All Firms					Multi-Unit Firms				
	Mean (1)	SD (2)	P1 (3)	Median (4)	P99 (5)	Mean (6)	SD (7)	P1 (8)	Median (9)	P99 (10)
A. 1990-2010 NETS Sample										
Multi-unit firm	0.06	0.24	0	0	1					
Number of counties	1.17	1.44	1	1	5	3.71	5.10	2	2	24
Employment	104.44	720.89	10	25	1379	869.83	2694.03	25	272	9764
Observations					3,846,245					241,206
B. 2002 Matched NETS-HH Sample										
Multi-unit firm	0.25	0.43	0	0	1					
Number of counties	1.71	2.88	1	1	11	3.82	5.20	2	2	23
Employment	338.68	710.46	10	160	3239	776.23	1201.61	45	411	5465
Internet	0.88	0.33	0	1	1	0.90	0.30	0	1	1
Intranet	0.45	0.50	0	0	1	0.55	0.50	0	1	1
Observations					10,138					2,557

Notes: Panel A presents summary statistics of firm characteristics and geographic span of control from 1990-2010 NETS data. Column (1)–(5) correspond to all firms in the sample. Column (6)–(10) correspond to multi-unit firms; that is, firms with production in multiple counties. Panel (B) presents summary statistics from the 2002 matched NETS-HH sample. Intranet and Internet are dummy variables that are set to one if a firm is connected to Intranet or Internet, respectively.

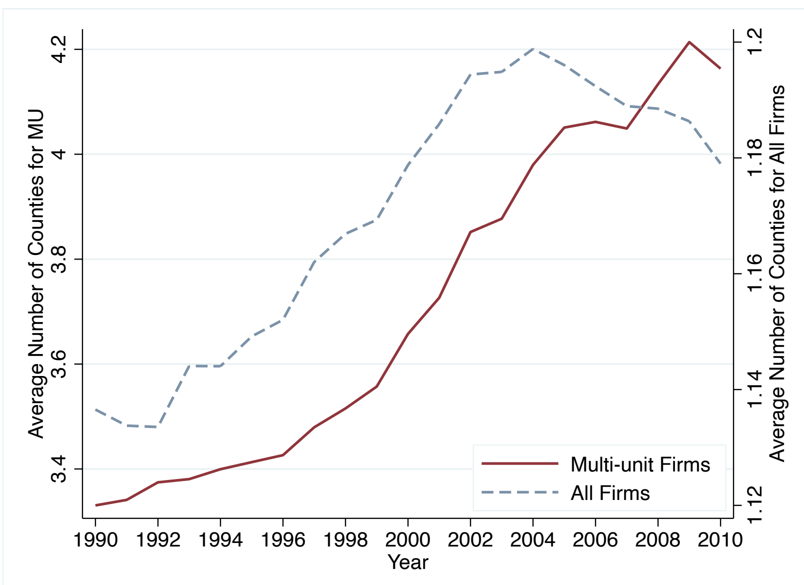
2.2 Stylized Facts

I document two stylized facts. First, firms in the US manufacturing sector have increased their geographic span of control, especially those with multiple production sites. Second, Firms with Intranet are associated with a larger geographic span of control.

2.2.1 Fact I: Increasing firms geographic span of control

Panel A in Figure 1 plots the average number of counties covered by firms during 1990–2010. The red line represents multi-unit firms who experienced a significant increase over the past two decades, especially after the mid-1990s. The average number of counties for these firms increased from 3.3 to 4.2 over the past two decades, which is translated into a 25% increase. The dashed blue line represents all firms that saw an increase of 3.7% during the same period.[6] It is worth noting that a median multi-unit firm remains operating in 2 counties. Firms at the 75th percentile increased the coverage of counties from 3 to 4 since the early 2000s. Moreover, firms at the 99th percentile almost doubled their footprints from 17 to 32 counties during the past twenty years.

Figure 1: Increasing Average Number of Counties Per Firms During 1990-2010



Notes: This figure plots the average number of counties of firms using an unbalanced panel in NETS from 1990 to 2010. The red solid line represents the averages for multi-unit firms with scales on the left y-axis. The blue dashed line represents the averages for all firms with scales on the right axis.

[6]Barnatchez, Crane, and Decker (2017) finds that NETS see an increase in the coverage, especially of small firms, in recent years, which could lead to a decrease in the share of multi-unit firms. In data, we see the fraction of multi-unit firms are around 6% throughout the sample period.

2.2.2 Fact II: Communication costs and firm geographic span of control

I use the NETS-HH matched sample in 2002 to show the relationship between within-firm communication costs and firms' geographic expansion. In particular, I use a firm's Intranet adoption as a proxy for the firm's internal communication cost. I present the results in a regression framework.

$$\text{FirmSpanControl}_i = \alpha + \beta \text{INTRANET}_i + \boldsymbol{X}_i \gamma + \delta_j + \varepsilon_i, \tag{1}$$

where the dependent variable is a measure of firm span of control, INTRANET is an indicator that equals to one if a firm has installed Intranet, $\boldsymbol{X}_i$ is a vector of firm-specific characteristics including logarithm of lagged employment, exporting status, importer status, and the Internet connectivity. Since different industries may differ in their technology intensity, I also control for industry fixed effects.[7]

Table 2 reports the regression results. The first two columns uses the number of counties a firm has as dependent variable. Column (1) shows that, on average, a firm that installed Intranet is associated with 0.65 more counties, or equivalently a 35% increase relative to the average. Unsurprisingly, the estimates is smaller after controlling firm characteristics, but still implies a 19% larger number of counties for Intranet adopters. Compared to the significant effect of Intranet, a firm's connectivity with the Internet plays a minor role in the firm's geographic span of control. Column (3)–(4) look at the number of counties for multi-unit firms and find a comparable effect of the Intranet. However, the coefficient on the Intranet becomes relatively small and statistically indistinguishable from zero after controlling for employment and other firm characteristics. Finally, column (5)–(6) use an indicator of multi-unit firms as the dependent variable. Column (6) shows that firms with Intranet installed are more likely to be multi-unit firms by 5.6 percentage point. This translates to a 19% higher likelihood, taken into account that 29 percent of firms are multi unit.

These data patterns show that firms with more advanced ICT (i.e., Intranet), which is supposed to reduce within-firm communication costs, are associated with larger geographic span of control. This positive correlation may be because more productive firms are more likely to upgrade ICT as well as expand geographically. In the next section, I leverage plausible exogenous variations from a historical event, trying to document a causal relationship between ICT and firm geographic expansion.

[7] In the baseline specification, industry is at two-digit SIC level. The results are robust when we define industry at four-digit SIC level.

Table 2: Relationship Between Intranet Adoption and Firm Geographic Span of Control

	#Counties of All Firms		#Counties of MU Firms		MU Indicator	
	(1)	(2)	(3)	(4)	(5)	(6)
Intranet	0.650***	0.356***	1.087***	0.291	0.114***	0.056***
	(0.078)	(0.080)	(0.251)	(0.256)	(0.011)	(0.010)
Lag Log(Emp)		1.015***		2.056***		0.167***
		(0.036)		(0.121)		(0.005)
Exporter		0.463***		0.193		0.113***
		(0.090)		(0.259)		(0.011)
Importer		0.156*		0.112		0.052***
		(0.081)		(0.260)		(0.010)
Internet		0.046		0.066		0.040**
		(0.129)		(0.475)		(0.016)
Observations	7153	6785	2028	1962	7153	6785
Avg. Dep.	1.851	1.873	4.000	4.018	0.284	0.290
R^2	0.025	0.158	0.030	0.173	0.045	0.267
Industry FE	Y	Y	Y	Y	Y	Y

Notes: This table uses the 2002 matched NETS-HH sample to estimate regressions of the following form:

$$\text{FirmSpanControl}_i = \alpha + \beta \text{INTRANET}_i + \boldsymbol{X}_i \gamma + \delta_j + \varepsilon_i,$$

where the dependent variable is the number of counties for column (1)–(4) and is a dummy variable set to one for multi-unit firms for column (5)–(6). INTRANET is a dummy variable set to one if a firm has installed firm-wide Intranet. X_i is vector of firm characteristics including logarithm of lagged employment, exporter status, importer status, and a dummy variable set to one if a firm is connected to the Internet. Industry fixed effects δ_j are included in all specifications. Industry is defined at two-digit SIC level. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

3 Reduced-Form Evidence from Internet Privatization

This section shows that enhancements of information and communication technology plays an important role in facilitating firms' geographic expansion. I exploit natural experimental variation from a milestone in the US Internet history—the Internet privatization. The explosive development of Internet following the privatization allowed firms to widen their geographic span of control.

3.1 The Internet Privatization

The development of Internet has been a key part in the recent history of information and communication technology. From the early dial-up access to the broadband nowadays, the improving Internet, including faster speed and various applications, has changed every aspect of business activities. Prior to 1995, the Internet was not anything like what it is nowadays. The foundation of the Internet today is the National Science Foundation Network (NSFNET), the first high-speed internet backbone in the US since 1986 and was operated by the government through National Science Foundation (NSF). By the early 1990s, the NSFNET connected sixteen node sites across the US. These node locations reflected historical reasons due to military bases and university locations.[8] As showed in Figure 2, these nodes were located at Ithaca, Princeton, San Diego, Champaign, Boulder, Lincoln among other locations. Additionally, the NSFNET utilized a three-tiered architecture. Each node was connected to regional networks that were in turn linked to the backbones.

The NSFNET was originally devoted for the research and higher education community, so commercial use was restricted at the beginning. With exploding interest and demand from the commercial side, however, this restriction was gradually lifted up. Finally, the Internet—once a government asset—was handed over to the private sector in the early 1990s. The Internet privatization was finalized on April 30, 1995. Following the privatization, "Internet gold rush" started.[9] I exploit this historical event and use the privatization of the NSFNET as a natural experiment. As Greenstein (2015) comments on the role of the privatization in catalyzing the explosive development in Internet-related industries, *"The complexity of privatization made it difficult for any observers to grasp the consequences of the NSF privatization... A commercially viable working prototype could not exist until the NSF finished announcing its privatization plan."*[10]

The slow-growing number of Internet Service Providers before 1995 and the explosive market shortly after 1995 reflects the critical role of the Internet privatization. It further justifies my empirical strategy that uses this event as an exogenous shock to the Information and communication technology.

3.2 Empirical Approach

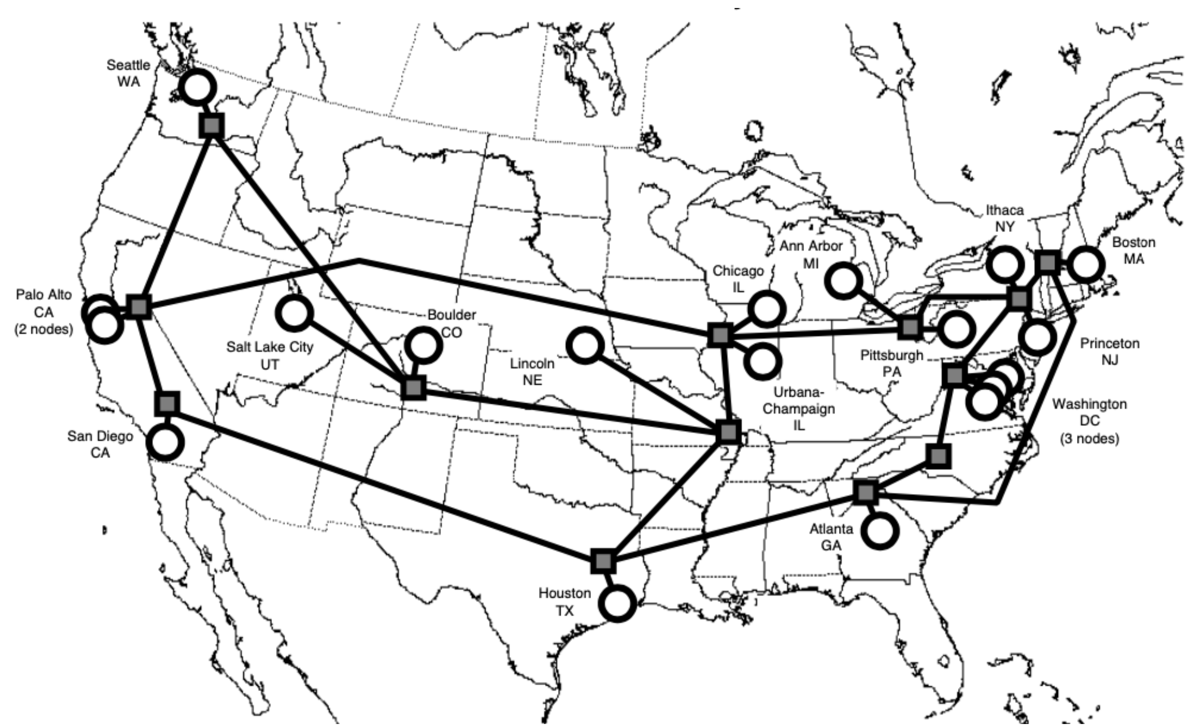
I use the distance from a firm's headquarter to the nearest node site of the NSFNET to measure firms' exposure to the Internet privatization. Locations closer to these nodes had better infrastructure such as underground fiber optic lines, which was crucial for the Internet access. Businesses often access the Internet through leased lines, which requires physical lines

[8]Several of the NSFNET node were inherited from the Advanced Research Projects Administration Net (ARPANET) – the predecessor of NSFNET, a military-funded internet backbone run by Department of Defense.

[9]Appendix section B provides more details on the development and privatization of the NSFNET.

[10]The conversation concerning the privatization of internet started from the beginning of the 1990s. There were policies around 1992 that allowed commercial business to connect to the internet. Nevertheless, the final privatization of the Internet in 1995 did play as a catalyst to the "Internet gold rush."

Figure 2: Map of the NSFNET Network 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 shaded square represent interior nodes connecting the exterior nodes. The black lines represent traffic flows on the network. This figure is downloaded from GenBank database at the San Diego SuperComputer Center: `ftp://genbank.sdsc.edu/pub/sdsc/anr/maps/NSFNET/t3.ps`

near the companies. As the construction and installation of circuits is one major cost for internet service providers, costs of the Internet access for businesses were lower if they were in locations with better infrastructure.[11] In addition, many NSFNET nodes are located on campus inside universities where more talents were able to provide ICT services.

My empirical approach builds on the idea that firms located closer to the Internet backbone nodes were able to better grasp the benefits following the Internet privatization.

[11]McKnight and Bailey (1998) documents that costs of leased lines and routers accounted for 80% of total NSFNET costs. Bloom et al. (2014) uses country-level variations in leasing telephone lines to instrument for firms' probability of adopting Intranet; they also use the distance to the headquarter of SAP – a world leading ERP provider – to measure firms' probability of adopting ERP softwares. Forman et al. (2012) uses county-level variations of the number of nodes for the ARPANET—a predecessor of the NSFNET—as an instrument for local advanced IT investment by businesses.

Reduced-form analysis takes the form of a difference-in-difference regression framework:

$$\text{FirmSpanControl}_{ist} = \alpha_i + \beta_t \text{DistToNode}_s + Z_{ct}\lambda + \delta_{jt} + \eta_{ft} + \varepsilon_{ist}, \tag{2}$$

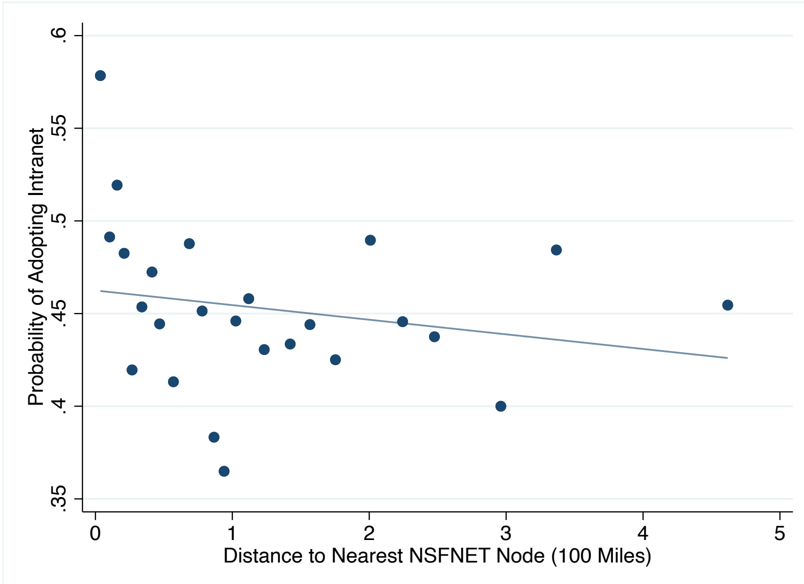
where i denotes firms, s denotes headquarter locations at the ZIP code level, and t denotes years. $\text{FirmSpanControl}_{ist}$ is a measure of firm geographic span of control, α_i is firm fixed effects, DistToNode_s is the distance from a firm's headquarter to the nearest NSFNET node. The coefficient of interest is β_t, which measures the differential span of control for firms with different distances to the nodes for each year. To control for other potential local shocks that affect firms' expansion decisions, I include a set of county-year-specific characteristics including logarithm of population, logarithm of median household income, percentage of black population, percentage of the elderly over 65 years old, and percentage of adults with a bachelor's degree. I include industry-year fixed effects δ_{jt} to control for differential industry trends where industry is measured at the two-digit SIC level.[12] State-year fixed effects η_{ft} ease the concern that results are driven by differential expansion patterns across locations, e.g., due to state fiscal policies.

Local amenities might affect firms' location choices (e.g. Suarez Serrato and Zidar, 2016). For instance, firms with expansion plans may choose to locate their headquarters at locations with better Internet infrastructure. To eliminate concerns regrading endogenous location choice of the headquarter, I focus on a balanced panel with firms existing throughout the sample period from 1990 to 2007 and those firms that had not changed their headquarter locations.

Although a complete panel of firms' ICT adoption is not available, I use the cross-sectional data of 2002 matched NETS-HH sample to provide first-stage evidence, showing that firms located closer to the NSFNET nodes are more likely to adopt ICT post the Internet privatization. Such ICT-enabled applications as Intranet were unavailable before the privatization, so the adoption rates in 2002 also reflect changes in the likelihood of ICT adoption. Figure 3 presents the relationship between the fraction of firms that had adopted Intranet in 2002 and the distance to the nearest NSFNET nodes. The fitted line is downward sloping, demonstrating that the likelihood for firms of adopting Intranet decreases (increases) as firms are located further away (closer to) these nodes. While the matched sample is smaller than the full NETS data, it is reassuring to find a negative relationship between my exposure measure and ICT adoption. In the main reduced-form analysis, I use the panel data in NETS and exploit variations over time from the Internet privatization, which allows me to add firm fixed effects and a richer set of control variables.

[12] Results are robust when industry is measured at the four-digit SIC level.

Figure 3: Relationship Between Intranet Adoption and Distance to NSFNET Nodes



Notes: This figure is a binscatter of firms' Intranet adoption (i.e., a dummy variable that is set to 1 if a firm had adopted Intranet in 2002) on their distance to the nearest NSFNET node from the firms' headquarters. This figure uses observations in the 2002 matched NETS-HH sample.

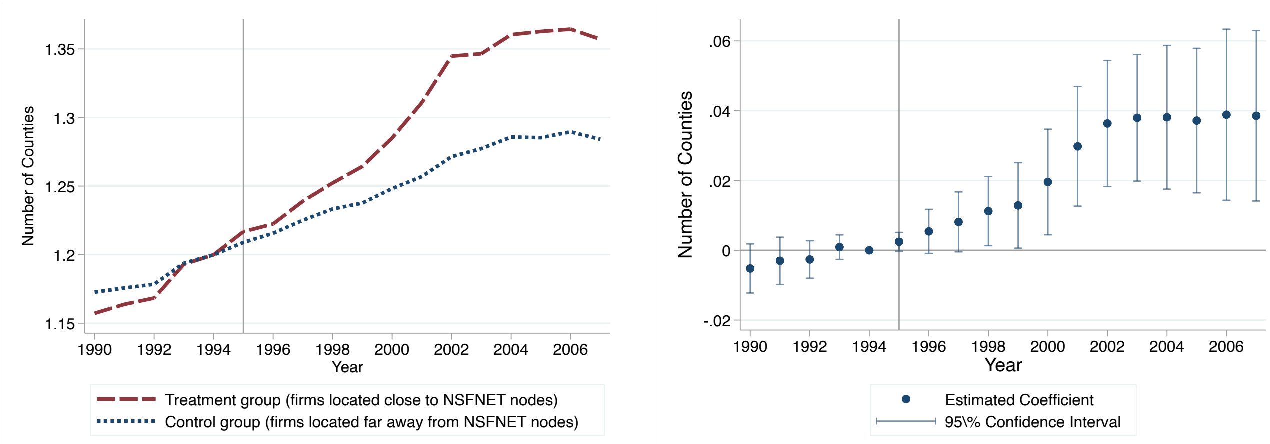
Graphical evidence The key identification assumption is that the Internet privatization did not coincide with other location-by-year shocks. To validate this assumption, I show graphical evidence that firms located close to the nodes had similar geographic coverage to those firms located farther away from the nodes. I sort firms into groups according to their distance to the nearest NSFNET node. Panel A in Figure 4 plots the average number of counties over time for firms in the top quartile (i.e., faraway locations) and the bottom quartile (i.e., close locations).[13] The red long-dashed lines correspond to firms in the bottom quartile—the treatment group—with an average distance of 20 miles to the node. Cook County and DuPage County in Illinois and Middlesex County in Michigan are examples in this group. The blue short-dashed lines correspond to those far away from the nodes—the control group—with an average distance around 400 miles to the node. Those far-away locations include counties such as Maricopa County in Arizona and Miami-Dade county in Florida among others. As showed in the figure, the two groups of firms had similar trends in the number of counties before 1995. After the Internet privatization, however, the trends diverge. While firms in both groups saw increase in the number of counties they cover, those firms that were located closer to the NSFNET nodes saw a larger rise.

[13]These averages are obtained by regressing the number of counties on a set of interaction between group dummies and year dummies, controlled for industry-year and state-year fixed effects.

Panel B quantify the differences between the two groups by plotting the estimated coefficients β_t in Equation 2. Many of these estimates are negative, indicating that firms located *closer* to the NSFNET nodes cover *more* counties. For easier presentation, I plot $-\beta_t$ and normalize by that for year 1994, i.e., $\beta_t - \beta_{1994}$. The coefficients are precisely estimated around zeros before the Internet privatization, indicating that firms with different distances to the nodes have similar trends prior to the privatization. After 1995, firms located closer to the nodes gradually saw an increasing number of counties. The gradual increase in firms' footprints may reflect the time for integrating ICT system into firms' operation, or the time to set up new establishments. The estimates are statistically significant at 5 percent level after 2000 and are stable since the early 2000s.

Figure 4: Reduced-Form Effects of the Internet Privatization

Panel A. Levels Panel B. Differencens



Notes: These figures shows the effects of the Internet privatization on the number of counties using a balanced sample in NETS from 1990 to 2007. Panel A plots the average number of counties for firms that are sorted according to their distance to the NSFNET nodes. The red long-dashed line represents firms in the lowest quartile; that is, firms located close to the NSFNET nodes (treatment group). The blue short-dashed line represents firms in the highest quartile; that is, firms located faraway from the nodes (control group). These are the sample averages, controlled for industry fixed effects at two-digit SIC level and state fixed effects. To ease comparison, I align the average number of counties for the treatment and control groups to the sample average in 1994. Panel (B) plots the coefficients β_t in event study regressions of the following form:

$$Y_{ist} = \alpha_i + \beta_t \text{DistToNode}_s + Z_{ct}\lambda + \delta_{jt} + \eta_{ft} + \varepsilon_{ist},$$

where the dependent variable is the number of counties for firm i at location s in year t, and location is measured at the ZIP code level. α_i is firm fixed effect, DistToNode_s is the distance from location s to the nearest NSFNET node, Z_{ct} is a vector of county-year characteristics including logarithm of population, logarithm of median household income, percentage of black population, percentage of the elderly over 65 years old, and percentage of adults with a bachelor's degree of higher, δ_{jt} is industry-year fixed effect, η_{ft} is state-year fixed effect, and ε_{ist} is the error term. To ease comparison, I normalize the coefficients to that of year 1994. Standard errors are clustered at the firm level.

Taken together, the years before the privatization provide graphical evidence for placebo tests and suggest that our identification assumption holds.

3.3 Regression Results

Table 3 reports the estimates from the difference-in-difference regressions of the following form:

$$\text{FirmSpanControl}_{ist} = \alpha_i + \beta \text{DistToNode}_s \times \text{Post}_t + Z_{ct}\lambda + \delta_{jt} + \eta_{ft} + \varepsilon_{ist}. \tag{3}$$

Here, Post_t is a dummy variable that equals to one for years from 1995 onwards. Column (1) and (2) show that firms located closer to the NSFNET nodes experienced larger expansion. The coefficient on the interaction term between the distance to the node and post-reform dummy is estimated to be -0.026 when we control for county characteristics, indicating that firms that were located 100 miles *closer* to the nodes were associated with 0.026 *more* counties after the Internet privatization. To interpret the magnitude, note that the average distance to the nodes is around 130 miles. On average, firms increased their coverage by 0.034 (= 0.026 × 1.3) counties after the Internet privatization. Compared to an average of 1.25 counties per firm, this translates into a 2.7% = 0.034/1.25 × 100 increase. Another way to interpret the magnitude is to compare to the overall increase in firms' coverage after the privatization. The average number of counties increased from 1.21 to 1.30 units during the post privatization period during 1995 to 2007. That is, the predicted increase by the Internet privatization accounts for 37.8% = 0.034/0.09 × 100 percent of the overall increase. It is also worthwhile noting that local education level facilitates firm expansion. In particular, the average number of counties increases by 0.17 units, or equivalently 13.6% = 0.17/1.247 × 100%, as the share of population with a bachelor's degree increases by 10 percentage point. This positive relationship indicates that more skilled labor might help increase firm span of control.

Column (3)–(4) focus on those firms that had been multi-unit throughout the sample period. The coefficient on the interaction term is consistently estimated around 0.45–0.49, which is larger in magnitude than that using all firms. As the average distance for multi-unit firms is at 120 miles, this estimate indicate that average number of counties for multi-unit firms increased by 0.53 = 0.445 × 1.2 units. Taken into account an average at 5.55 counties for multi-unit firms, this estimate is equivalent to a 9.6% = (0.53/5.55 × 100%) increase. The larger effect for multi-unit firms compared to that on all firms may be because multi-unit firms have more experience in managing multiple establishments, which allows them to expand to a greater degree when new technology arrives. As another measure, I also consider a dummy variable that is set to one for multi-unit firms. Showed in column (5)–(6), the

Internet privatization increased the likelihood for single-unit firms to expand production in multiple locations. As the fraction of multi-unit firms is 8.2 percent, the estimated coefficient at 0.002 is translated into $3.2\% = 0.002 \times 1.3/0.082$ increase.

Robustness. One may concern that the number of counties per se does not capture the geographic expansion. For instance, a firm can open a new establishment in a nearby county and managers can drive between the headquarter and establishments for daily visit. To address this concern, I consider three other measures of firm geographic span of control: the number of counties that are non-drivable, i.e., those counties located over 250 miles away from the firm's headquarter; the number of counties that are out of the headquarter's state; inverse hyperbolic sine transformation of the average distance from the establishments to a firm's headquarter, weighted by the establishment's employment share. Column (1)–(4) columns in Table 17 report the results for the number of non-drivable and out-of-state counties, respectively. The estimated coefficients are consistent with the baseline results, reassuring that the number of counties does reflect firm expansion across space. Column (5)–(6) suggest a positive impact of the Internet privatization on within-firm distance, while the magnitude is small and becomes statistically insignificant after controlling a richer set of county characteristics. In the appendix Table 18, I weight the baseline regressions by the firm's employment, putting more weights on big firms. It might be unsurprising that, on one hand, the coefficients are larger when the dependent variable is the number of counties, indicating that bigger firms experienced larger expansion. On the other hand, the coefficient becomes smaller and statistically insignificant when the dependent variable is an indicator of multi-unit firms, where the switching from single-unit to multi-unit is driven by relatively small firms.

Table 3: Estimated Effects of the Internet Privatization on Firm Expansion

	#Counties of All Firms		#Counties of MU Firms		MU Indicator	
	(1)	(2)	(3)	(4)	(5)	(6)
DistToNode X Post	-0.034***	-0.026***	-0.492**	-0.445**	-0.002**	-0.002*
	(0.007)	(0.007)	(0.204)	(0.211)	(0.001)	(0.001)
Log(Pop)		-0.073		0.313		0.010
		(0.061)		(1.276)		(0.010)
Log(Median Income)		0.014		-0.122		0.054***
		(0.096)		(2.523)		(0.017)
%Bachelor		0.017***		0.085		0.000
		(0.003)		(0.054)		(0.000)
%Black		0.005**		0.047		0.000
		(0.002)		(0.055)		(0.000)
%Over65		0.004		0.151		0.000
		(0.004)		(0.102)		(0.001)
Observations	911034	911034	34308	34308	911034	911034
Clusters(firms)	50613	50613	1906	1906	50613	50613
Avg. Dep.	1.247	1.247	5.548	5.548	0.082	0.082
R^2	0.825	0.825	0.834	0.834	0.785	0.785
Industry-Year FE	Y	Y	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y	Y	Y

Notes: This table uses 1990-2007 NETS to estimate difference-in-difference regressions of the form:

$$Y_{ist} = \alpha_i + \beta_t \text{DistToNode}_s + Z_{ct}\lambda + \delta_{jt} + \eta_{ft} + \varepsilon_{ist},$$

where the dependent variable is a measure of firm geographic span of control for firm i at location s in year t, and location is measured at the ZIP code level. α_i is firm fixed effect, DistToNode_s is the distance from location s to the nearest NSFNET node, Post_t is a dummy variable set to 1 for years since 1995, Z_{ct} is a vector of county-year characteristics, δ_{jt} is industry-year fixed effect, η_{ft} is state-year fixed effect, and ε_{ist} is the error term. The dependent variable is the number of counties a firm has for column (1) and (2), the number of counties a multi-unit firm has for column (3) and (4), and a dummy variable set to 1 for multi-unit firms for column (5) and (6). Firm fixed effect, industry-year fixed effect and state-year fixed effects are included in all columns. Column (2), (4), and (6) control for additional county characteristics. Standard errors are clustered at the firm level. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4 Model

I add endogenous within-firm communication costs to an industry equilibrium trade model where firms can produce products at multiple locations (based on Tintelnot, 2017), by allowing firms to adopt advanced ICT that lowers communication costs between headquarters and production sites.

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 the location $i \in [0, m_s]$, where m_s is the mass of the firms in location s. The representative consumer sells labor in a perfect competitive market and maximizes CES preference. The settings on firms follow Tintelnot (2017), assuming each firm i produces a continuum of differentiated varieties $\omega \in [0,1]$ which are tradable across locations. Each product is then indexed by a firm-variety combination (i, ω). Firms compete monopolistically in each product market.

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

4.1 Demand

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

$$U_k = \left(\sum_{o=1}^{N} \int_0^{m_o} \int_0^1 y_{ok}(i,\omega)^{\frac{\sigma-1}{\sigma}} d\omega di \right)^{\frac{\sigma}{\sigma-1}}, \tag{4}$$

where $y_{ok}(i, \omega)$ is the output of variety ω shipped to market k by firm i which is headquartered at o. Here, I assume that the elasticity of substitution is identical among varieties within and across firms. In the benchmark model, I fix the set of firms in each location and abstract away from firms' entry decisions. This assumption is consistent with my empirical analysis which focused on a balanced sample of firms which existed throughout the sample period.

Given prices and the consumer's expenditure on manufacturing goods E_k, we can solve the consumer's problem and get the demand from market k for firm i variety ω:

$$y_{ok}(i,\omega) = E_k P_k^{\sigma-1} p_{ok}(i,\omega)^{-\sigma}, \tag{5}$$

where P_s is the ideal price index of market k defined by

$$P_k = \left(\sum_{o=1}^{N} \int_0^{m_o} p_{ok}(i)^{1-\sigma} di \right)^{\frac{1}{1-\sigma}}, \text{ and where } \; p_{ok}(i) = \left(\int_0^1 p_{ok}(i,\omega)^{1-\sigma} d\omega \right)^{\frac{1}{1-\sigma}}. \tag{6}$$

The price index $p_{ok}(i)$ is firm-specific and summarizes the prices charged to market k of all varieties produced by firm i which is headquartered at o. Local price index P_k summarizes the prices charged to market k by all firms in the economy.

4.2 Production Technology

Each firm is endowed with an establishment in their birth location, called *headquarter*, and can set up additional establishments in other locations with up to one establishment at each location.

Production at the establishment. Production takes place at establishments. The value-added production function is Cobb-Douglas and is constant return to scale (CRS). Productivity include two components: one is firm-specific productivity that affects all the firm's establishments, and the other is establishment-specific productivity. Labor is the only input here. Production in any establishments, including the headquarter, incurs an iceberg type production loss γ_{ios}: Producing one unit of output requires γ_{ios} units of labor. Potential sources for the production loss include physical shipping costs as well as efficiency loss in the communication process. That said, Atalay et al. (2014) uses US Census data and finds that inter-plant shipping is rare. Thus in the following of the paper, γ_{ios} is referred to as communication costs. Specifically, the production function takes the following form:

$$y_{ios} = z_i \varepsilon_{is} \gamma_{ios}^{-1} l_{ios}, \tag{7}$$

where z_i is productivity of firm i, ε_{is} is the establishment-specific productivity at location s and l_{ios} is the local labor. Firm-specific productivity z_i is independently and identically drawn from log-normal distribution $G(z)$. Establishment-specific productivity ε_{is} is drawn from a location-specific distribution $F_s(\varepsilon)$ and is independently and identically distributed across establishments at location s. Particularly, I assume that ε_{is} follows the Frećhet distribution with shape parameter θ and scale parameter T_s; that is:

$$F_s(\epsilon) = \exp(-(\epsilon/T_s)^{-\theta}), \tag{8}$$

where the scale parameter T_s determines the state of technology at location s, and the shape parameter θ determines the dispersion of establishment productivity draws.

Communication cost and ICT. The communication cost is firm-specific and decreases in the firm's ICT level. In addition, the communication cost may be affected by the firm's headquarter and establishment's locations such as distance between the two locations. Specifically, I assume $\gamma_{ios} = \gamma_{os}(\varphi_i)$, where φ_i denotes the firm i's ICT level. Firms that adopt a higher ICT level are associated with lower communication costs.

Let o denote the firm's headquarter location. Index firms headquartered at o by their productivity z and ICT level φ. For firm (φ, z) that is headquartered at o, its unit cost of producing a variety ω at establishment in location s and shipping to market k is

$$c_{oks}(\omega, \varphi, z) = (z\varepsilon_s(\omega))^{-1}\gamma_{os}(\varphi)w_s\tau_{sk}, \tag{9}$$

which summarizes the production efficiency, costs of input and market access to the destination market. In particular, as the communication cost $\gamma_{os}(\varphi)$ decreases in the firm's ICT level φ, firms with a higher ICT level are also associated with lower unit costs.

Fixed costs. As mentioned earlier, a firm can set up multiple establishments besides its headquarter to expand production, which is subject to fixed costs f_{ios}^X where i denotes firm, o denotes the firm's headquarter and s denotes the establishment location. Additionally, firm i pay a fixed cost f_i^{ICT} if it chooses to adopt a higher level ICT. Fixed costs f_{ios}^X and f_i^{ICT} are firm-specific because the expansion decisions and ICT adoption vary across firms with similar characteristics. As fixed costs and their forms are unobservable from data, I assume both fixed costs are paid in the numeraire with the same price across locations.

4.3 Firm's Optimization Problem

Firms decide whether to adopt higher ICT level, choose optimal sets of locations for production, hire labor, produce a continuum of varieties and serve destination markets. I use backward induction to solve the firm's optimization problem. I first derive the firm's optimal profit conditional on a set of locations. Then, I take a step back and solve the firm's optimal locations choices. Finally, I solve the firm's ICT adoption decision.

4.3.1 Production given a set of establishment locations and state of ICT

Let the set of locations $S \in \mathscr{S}$ be fixed. For each market k, the firm chooses one of its establishment $s \in S$ that has lowest unit cost $c_{oks}(\omega, \varphi, z)$ to serve market k. So the actual unit cost of variety ω produced by firm (φ, z) to market k is

$$c_{ok}(\omega, S, \varphi, z) = \min_{s \in S} c_{oks}(\omega, \varphi, z), \tag{10}$$

where $c_{oks}(\omega, \varphi, z)$ is defined in Equation (9). As the firm produces a continuum of varieties $\omega \in [0, 1]$ and establishment-specific productivity draws $\varepsilon_s(\omega)$ follow Frećhet distribution and are independently distributed across varieties and locations, the share of varieties produced at establishment in location $s \in S$ equals to the sales share of any establishment $s \in S$

relative to the total firm's sales to market k:

$$\zeta_{ok\leftarrow s}(S,\varphi) = \frac{T_s^{\theta}(\gamma_{os}(\varphi)w_s\tau_{sk})^{-\theta}}{\Phi_{ok}(S,\varphi)}, \tag{11}$$

where T_s is the scale parameter of establishment productivity distribution in location s, θ is the corresponding shape parameter, and $\Phi_{ok}(S,\varphi)$ is defined by

$$\Phi_{ok}(S,\varphi) = \sum_{s'\in S} T_{s'}^{\theta}(\gamma_{os'}(\varphi)w_{s'}\tau_{s'k})^{-\theta}. \tag{12}$$

$\Phi_{ok}(S,\varphi)$ captures the "production potential" of the set of locations S to serve market k for firms headquartered at o and with ICT level φ. It summarizes the locations' states of technology, wages at both the headquarter and establishments locations, the shipping cost – or market access – to market k and communication cost between the headquarter and establishments. More importantly, the production potential depends on a firm's ICT level. Given the same headquarter, set of establishments locations and market location, firms with a higher ICT level have larger production potentials.

Due to the CES demand, the firm charges a constant markup relative to the marginal cost. That is, the price charged to market k by the firm is $p_{ok}(\omega,S,\varphi,z) = \frac{\sigma}{\sigma-1}c_{ok}(\omega,S,\varphi,z)$, where $c_{ok}(\omega,S,\varphi,z)$ is the lowest unit cost defined in Equation (10). Then, we can get the firm price index to market k:

$$p_{ok}(S,\varphi,z) = \left(\int_0^1 p_{ok}(\omega,S,\varphi,z)^{1-\sigma}d\omega\right)^{\frac{1}{1-\sigma}} = \frac{\sigma}{\sigma-1}\tilde{\Gamma}^{\frac{1}{1-\sigma}}z^{-1}\Phi_{ok}(S,\varphi)^{-\frac{1}{\theta}}, \tag{13}$$

where $\tilde{\Gamma} = \Gamma\left(\frac{\theta-\sigma+1}{\theta}\right)$ and the production potential $\Phi_{ok}(S,\varphi)$ is defined in Equation (12).

We can further derive the firm's profit from market k is

$$\pi_{ok}(S,\varphi,z) = \frac{\sigma^{-\sigma}}{(\sigma-1)^{1-\sigma}}\tilde{\Gamma}z^{\sigma-1}E_kP_k^{\sigma-1}\Phi_{ok}(S,\varphi)^{\frac{\sigma-1}{\theta}}, \tag{14}$$

where E_k is the consumer's total spending on manufacturing goods and P_k is the ideal price index at location k.

Summing the expected profit over all destination markets, we have that the firm's total profit, net of fixed costs of expansion, is:

$$\pi_o(S,\varphi,z) = \frac{\sigma^{-\sigma}}{(\sigma-1)^{1-\sigma}}\tilde{\Gamma}z^{\sigma-1}\sum_{k=1}^{N}E_kP_k^{\sigma-1}\Phi_{ok}(S,\varphi)^{\frac{\sigma-1}{\theta}} - \sum_{s=1}^{N}\mathbb{1}[s\in S]f_{os}^X. \tag{15}$$

The set of locations S affects the firm's total production profits through the production potential $\Phi_{ok}(S, \varphi), \forall k$ and fixed costs of setting up establishments.

4.3.2 Optimal Set of Locations and ICT Adoption

Firms choose the optimal ICT level and also the optimal set of locations to maximize their net profits. Particularly, the firm's problem is

$$\pi_o(z) = \max_{\varphi \in \{\underline{\varphi}, \overline{\varphi}\}} \left\{ \max_{S \in \mathscr{S}} \pi_o(S, \varphi, z) - f^{ICT} \mathbb{1}[\varphi = \overline{\varphi}] \right\}, \tag{16}$$

where $\pi_o(S, \varphi, z)$ is the firm's profit given a set of production locations S, defined in Equation (15). Additionally, the inner maximization on S is a discrete choice problem involving a large number of choices (2^{N-1} in this case). I apply the methodology developed in Arkolakis and Eckert (2017) to solve this combinatorial discrete choice problem.

Communication technology revisited

From here on, I work with a simple yet flexible communication technology where the communication cost is decomposed into the product of two terms:

$$\gamma_{os}(\varphi) = h(\varphi) d_{os}, \tag{17}$$

where the first term is a function of the firm's ICT level φ and $h(\cdot)$ is decreasing in φ. Better ICT technology reduces the communication cost. The second term captures exogenous factors that might affect communication cost between the two locations. With this technological assumption, we can further decompose a firm's production potential as $\Phi_{ok}(S, \varphi) = \tilde{\Phi}_{ok}(S)/h(\varphi)$, where $\tilde{\Phi}_{ok}(S) \equiv \sum_{s \in S} T_s^{\theta} (w_s \tau_{sk} d_{os})^{-\theta}$ depends on the firm's locations choice (S) and other exogenous terms (to the firm). Combined with Equation (15), one can show that improving ICT is equivalent to increasing the firm's *effective* productivity $\tilde{z} \equiv z/h(\varphi)$, $h'(\varphi) < 0$.

In addition, technological upgrading and geographical expansion are complementary to each other. Consider the case where a single-unit firm headquartered at o. The firm adds establishment at s if and only if the difference in gross profits exceeds the fixed cost of setting up an additional establishment:

$$\tilde{\Gamma} \left(\frac{z}{h(\varphi)} \right)^{\sigma - 1} \sum_{k=1}^{N} E_k P_k^{\sigma - 1} \left(\left(\tilde{\Phi}_{ok}(\{o, s\}) \right)^{\frac{\sigma-1}{\theta}} - \left(\tilde{\Phi}_{ok}(\{o\}) \right)^{\frac{\sigma-1}{\theta}} \right) \geq f_{os}^X,$$

where $\tilde{\Gamma} = \frac{\sigma^{-\sigma}}{(\sigma-1)^{1-\sigma}}\Gamma\left(\frac{\theta-\sigma+1}{\theta}\right)$. The right hand side is the benefit of expanding to location s. All else held constant, the benefit is increasing in the firm's ICT level (φ). Firms with better ICT have higher likelihood of expanding.

Similarly, the firm adopts better ICT, i.e., $\overline{\varphi} > \underline{\varphi}$, if and only if:

$$\tilde{\Gamma}\left[\left(\frac{z}{h(\overline{\varphi})^{\alpha}}\right)^{\sigma-1} - \left(\frac{z}{h(\underline{\varphi})^{\alpha}}\right)^{\sigma-1}\right]\sum_{k=1}^{N} E_k P_k^{\sigma-1}\left(\tilde{\Phi}_{ok}(S)\right)^{\frac{\sigma-1}{\theta}} \geq f^{ICT}.$$

As a firm with establishments in both o and s has larger production potential to all markets than one with establishment only in o, i.e., $\tilde{\Phi}_{ok}(\{o,s\}) \geq \tilde{\Phi}_{ok}(\{o\})\ \forall k$, the firm also has larger benefit and thus likelihood of upgrading ICT.

4.4 Equilibrium

The quantitatively analysis is to the production of manufacturers. To fit into the entire economy, I assume a non-manufacturing sector selling homogeneous products which can be traded costless across locations. Consumers spent a constant fraction (η) of final expenditure (G_s) on manufacturing goods. In terms of labor market, I assume that labor is freely mobile across the two sectors. The non-manufacturing sector is larger enough such that the wage is pinned down by the productivity in the non-manufacturing sector and total income is exogenous.[14]

Let μ_o denote the measure of firms headquartered at location o, Z denote the support of firm productivity and Φ denote the support of ICT levels. Product market clearing condition is, $\forall s = 1, \cdots, N$,

$$\eta G_s = P_s Y_s, \text{ where } Y_s = \left(\sum_{o=1}^{N}\int_{Z\times\Phi} y_{os}(z,\varphi)^{\frac{\sigma-1}{\sigma}} d\mu_o(z,\varphi)\right)^{\frac{\sigma}{\sigma-1}} \tag{18}$$

and where $y_{os}(z,\varphi)$ is the sales to market s from firm that is headquartered at location o and has productivity z and ICT level φ. Employment in each location is, $\forall s = 1, \cdots, N$,

$$L_s = \int_{Z\times\Phi} l_{ss}(z,\varphi)d\mu_s(z,\varphi) + \sum_{o\neq s}\int_{Z\times\Phi} \mathbb{1}[s \in S_o(z,\varphi)]l_{os}(z,\varphi)d\mu_o(z,\varphi). \tag{19}$$

The first term is employment of local firms that are headquartered at the location, and the second term is employment of firms from other locations that set up establishments at the

[14]The assumptions on the labor market assume perfectly elastic labor supply, e.g., Eaton and Kortum (2002) and Antras et al. (2017).

location. An equilibrium is a vector of prices $\boldsymbol{P}$ that is consistent with firm optimization, and that clears product market for each location. The price indices affect total output not only through demand, but also through firms' ICT choices and thus the distribution of (z, φ), and firms' production locations choices.

Endogenous labor market. In the benchmark model, labor supply is perfectly elastic and wages are treated as exogenous. Key mechanisms, however, still carry through with endogenous labor markets regarding the equilibrium effects on firm expansion decisions. Consider the extreme case where labor supply is perfectly inelastic, which more discussion should be straddled. With endogenous labor markets, as the fixed cost decreases, labor demand increases, thus driving up the wages. The production potential term $\Pi_{ok}(S)$, which is a function of inverse of wages, decreases. Price indexes decreases and expenditure increases, which offset each other. The equilibrium effect, again, works as a counter force that reduces the appeal of geographic expansion.

5 Estimation

In the structural estimation, location is defined at the *census division* level based on both the patterns of firms expansion from data and the computation feasibility. When multi-unit firms add establishments in new counties, 63% of them are in different census divisions from the ones where firms are headquartered, guiding the choice of aggregating locations to the census division level.

Parameterization and calibration. Table 4 summarizes the parameters. I calibrate the elasticity of substitution across varieties (σ) to 4, the value centered in the range of estimates used in the international trade literature (see Head and Mayer (2014)). This value implies a markup around 33%. I also calibrate the shape parameter of the Fréchet distribution which governs the dispersion of establishment productivity draws (θ). This parameter affects the firms' location choices. Particularly, a larger value of θ implies less dispersion of local productivities. Locations become closer substitutes, so the benefit of having a larger set of production locations decreases. I calibrate its value to 3.6 which is the medium value from Eaton and Kortum (2002).[15]

Role of σ. The equilibrium effect is more prominent with larger elasticity of substitution across varieties (σ). As it's easier to substitute across varieties, the product markets become more competitive.

[15] Fajgelbaum et al. (2019) estimates θ to be in the range of 2.43-2.84 at the state level. Tintelnot (2017) and Hu and Shi (2019) assumes $\theta = 7$ for EU countries. Antras et al. (2017) uses the countries where US firms import from and estimates $\theta = 1.789$. Eaton and Kortum (2002) provides three measures of *theta* to be 2.84, 3.60 and 8.28.

Role of θ. The productivity dispersion does not affects the relative forces of the direct and indirect effects, but impacts the *level* of share of multi-unit firms.

Firm productivity follows log-normal distribution. I calibrate the mean of log productivity to -0.122, and dispersion to 0.767 from Guner et al. (2008).[16]

To ease the estimation, I further parameterize the trade cost, communication cost, and fixed costs f^X_{os} and f^{ICT}. Trade cost is log linear in the distance, i.e., $\tau_{ss'} = e^{\beta^\tau \log \text{Miles}_{ss'}}$, where $\text{Miles}_{ss'}$ is the distance between the two locations measured in miles. I calibrate β^τ to $1/\theta$ such that the elasticity of trade with respect to the distance is -1. That is,

$$\tau_{ss'}^{-\theta} = e^{-\log \text{Miles}_{ss'}}. \tag{20}$$

It is consistent with literature where the elasticity of the trade flows with respect to the distance is estimated around -1 (see Disdier and Head (2008)).

Recall that the communication cost decreases in the firm's ICT level and also depends on the firm's headquarter and establishment locations. I assume

$$\gamma_{os}(\varphi) = h(\varphi) d_{os}, \tag{21}$$

where φ is the firm's ICT level which is endogenously determined and $h(\cdot)$ is decreasing in φ. The second term captures exogenous factors that might affect communication cost between the two locations. As common in the literature, I assume the communication cost is log linear in the distance between the firm's headquarter and establishment level, with an elasticity β^d:

$$d_{os} = e^{\beta^d \log \text{Miles}_{os}}. \tag{22}$$

The exogenous communication cost at the headquarter is normalized to 1, i.e., $d_{oo} = 1$. To be consistent with data where I only observe firms' binary adoption of Intranet, I discretize ICT to two levels – low and high, i.e. $\varphi \in \{\underline{\varphi}, \overline{\varphi}\}$. The higher ICT level is normalized to 1, i.e., $\overline{h} \equiv h(\overline{\varphi}) = 1$. I estimate the communication cost associated with low ICT level $\underline{h} \equiv h(\underline{\varphi})$.

Fixed costs of setting up establishments are log-normally distributed with mean and variance μ^X_{os} and σ^X. Particularly, I assume the mean is linear in the distance between the

[16] Guner et al. (2008) uses 1997 US Economic Census to estimate firm productivity, which is called 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 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.

headquarter and establishment location: $\mu^X_{os} = \beta^X_1 + \beta^X_2 \log(\text{Miles}_{os})$. Fixed cost of adopting ICT is also log-normally distributed with mean and variance parameters μ^{ICT} and σ^{ICT}.

Estimation procedure. Parameters left for estimation include 9 scale parameter of the Frećhet distribution for establishment productivity in each location (T_s), the elasticity of exogenous communication cost (β^d), production loss with low ICT ($\underline{h}$), the mean and dispersion of fixed costs of setting up establishments ($\beta^X_1, \beta^X_2, \sigma^X$), and the mean and dispersion of fixed cost of adopting ICT (μ^{ICT}, σ^{ICT}). I estimate those parameters in two steps. In the first step, I use within-firm variations in the establishment employment shares to estimate β^d, as well as a vector of fixed effects of establishment locations to back out location-specific productivity T_s. In the second step, I estimate the rest of parameters using simulated method of moments.

Table 4: Parameters to Estimate

Description	Model variable	Parameterization	Parameter
Establishment productivity	ε_s	$\sim$ Frećhet(θ, T_s)	$T_s, s = 1, \cdots, 9$
Exogenous communication cost	d_{os}	$= e^{\beta^d \log \text{Miles}_{os}}$	β^d
Firm-specific communication cost	$\underline{h}$		$\underline{h}$
Fixed costs of setting up establishments	f^X_{os}	$\sim$ log-normal(μ^X_{os}, σ^X) $\mu^X_{os} = \beta^X_1 + \beta^X_2 \log(\text{Miles}_{os})$	$\beta^X_1, \beta^X_2, \sigma^X$
Fixed cost of adopting ICT	f_{ICT}	$\sim$ log-normal(μ^F_s, σ^F)	μ^{ICT}, σ^{ICT}

Notes: This table summarizes the parameters to estimate. Parameters not estimated: $\sigma = 4$, $\mu^z = -0.123$, $\sigma^z = 0.767$, $\theta = 3.6$,$\beta^\tau = 1/\theta = 0.278$.

5.1 Step I

Let a firm be headquartered at location o with a set of establishment locations S. By Equation (11), the sales share of establishment s to a market k is the establishment's contribution to the firm's production potential Φ_{oSk}. Ideally, I would like to have establishment-market-specific shipment for estimation. However, the NETS database only include establishment-level data, so I aggregate the shares to the establishment. The total sales share of an establishment to the firm's total sales is

$$\zeta_{oS,s} = T^\theta_s (d_{os} w_s)^{-\theta} \frac{\sum_k E_k P^{\sigma-1}_k \Phi^{\frac{\sigma-\theta-1}{\theta}}_{oSk} \tau^{-\theta}_{sk}}{\sum_k E_k P^{\sigma-1}_k \Phi^{\frac{\sigma-1}{\theta}}_{oSk}}. \tag{23}$$

The first term on the right-hand side is the establishment contribution to the firm's production potential, scaled by firm ICT level, which summarizes the production cost that is affected by local productivity T_s, wages both at the establishment and headquarter locations (w_o and w_s), as well as the exogenous communication cost between the two locations (d_{os}). Note that the firm's ICT φ is cancelled out as it is common to all establishments. The second term summarizes the shipping cost from the establishment locations to all markets – or "market access" – weighted by the market demand share.

Take the logarithm $\zeta_{oS,s}$, and normalize by the headquarter's sales share:

$$\log \tilde{\zeta}_{oS,s} = \underbrace{-\theta \log d_{os}}_{\text{communication cost}} \underbrace{+\log\left(\sum_k P_k^{\sigma} Y_k \Phi_{oSk}^{\frac{\sigma-\theta-1}{\theta}} \tau_{sk}^{-\theta}\right)}_{\text{market access}} + \xi_s + \xi_{oS}, \tag{24}$$

where $\log \tilde{\zeta}_{oS,s} = \log \zeta_{oS,s} - \log \zeta_{oS,o}$, ξ is an establishment-specific component, and ξ_{oS} is a headquarter-set-specific component. The sales data in the NETS have a high imputation rate and might be subject to measurement errors. To alleviate this concern, I instead use the *employment* share to conduct estimation. In Appendix D, I show that an establishment's employment share has the same representation as Equation (24).

Market access. As the firm's production potential Φ_{oSk} is headquarter-set-specific for each market k, the impact of an establishment's market access on its sales share depends on the firm geographic configuration, i.e. the firm's headquarter and other establishment locations. Thus, I approximate the market access term by

$$\begin{aligned} \log\left(\sum_k P_k^{\sigma} Y_k \Phi_{oSk}^{\frac{\sigma-\theta-1}{\theta}} \tau_{sk}^{-\theta}\right) &\approx (\phi + \phi_{oS}) \log\left(\sum_k \frac{N_k \bar{y}_k}{\sum_k N_k \bar{y}_k} e^{-\text{miles}_{sk}}\right) \\ &\equiv (\phi + \phi_{oS}) \log \overline{MA}_s, \end{aligned} \tag{25}$$

where N_k is the population of location k and $\bar{y}_k$ is the location's per capita income. That is, for each location I calculate a demand-weighted average distance from location s to other the markets. The coefficient includes both a constant (ϕ) and a headquarter-set-specific component (ϕ_{oS}), reflecting that the effect of shipping costs on establishment's sales share depends on the firm's headquarter location as well as the other establishment locations of the firm.

Combined with the parameterization of communication cost in Equation (22), the estimation equation is

$$\log \tilde{\zeta}^i_{oS,s} = -\theta\beta^d \log \text{Miles}_{os} + \phi_{oS} \log \overline{MA}_s + \xi_s - \xi_{oS} + \varepsilon^i_{oS,s}, \tag{26}$$

where i denotes firm, ξ_s and ξ_{oS} denote fixed effects of establishment locations and combinations of the headquarter and the set of locations. Error term $\varepsilon^i_{oS,s}$ captures other factors that affect communication and trade costs that are orthogonal to the firm's locations choice. Note that the common component of market access ($\phi \log \overline{MA}_s$) is absorbed by establishment location fixed effects. In particular,

$$\xi_s = \theta \log(T_s) - (\theta + 1) \log(w_s) + \phi \log \overline{MA}_s. \tag{27}$$

Given the value of θ, we can back out the value of β^d by $\hat{\beta}^d = -b^d/\theta$, where b^d is the coefficient on $\log \text{Miles}_{os}$ in Equaton (26).

Estimation results. The estimation sample include firms that exists through out the sample period from 1990–2007. Identification of the headquarter-set-specific coefficients ϕ_{oS} requires variations in the average market access $\overline{MA}_s$, excluding the headquarter location o, within the same headquarter-set combination. So I restrict to firms with operations at least three locations. I also include industry-year fixed effects to control for industry-specific trends, where industry is at the 2-digit SIC level.

Table 5 reports the estimation results. Column (1)–(2) uses only observations in 2002. Column (1) uses the employment share as dependent variable. The coefficient on the distance between the headquarter division and establishment division is estimated to be -0.258, indicating that a 10% miles reduction in distance is associated with 2.5% larger sales share at the establishment. This reduced-form coefficient correspond to the structural parameters $-\theta\beta^d$. As I calibrate θ to 3.6, the elasticity of communication cost with respect to distance β^d is $0.072 = (0.258/3.6)$. Column (2) uses the sales share as dependent variable, which delivers similar estimate. Column (3)–(4) use all observations from 1990-2007 and controls for year fixed effects. The coefficients are robust across different samples and specifications. Here, I interpret the coefficient on the distance between headquarters and establishments as communication cost. One can also interpret it as physical shipping costs if the establishment needs physically import production inputs such as intermediates from the headquarter. Nevertheless, Atalay et al. (2014) uses Commodity Flow Survey (CFS) and finds little inter-plant shipping even within vertically integrated firms.

Finally, the estimation also delivers a vector of estimated fixed effects of establishment locations for each year, which are used in the second-step estimation.

Table 5: First-Step Estimation Results

	Year 2002		All Years	
	Employment (1)	Sales (2)	Employment (3)	Sales (4)
$\log \text{Miles}_{os}$	-0.258***	-0.248***	-0.221***	-0.230***
	(0.079)	(0.081)	(0.048)	(0.049)
N	5099	5099	75174	75174
R^2	0.475	0.472	0.276	0.274
HQ-Set FE	Y	Y	Y	Y
EST Location FE	Y	Y		
Industry FE	Y	Y		
EST Location-Year FE			Y	Y
Industry-Year FE			Y	Y

Notes: This table presents the first-step estimation results. Dependent variable is the scaled within-firm employment and sales shares of each establishment. $\log \text{Miles}_{os}$ is the distance between the establishment and headquarter. Column (1)–(2) uses the 2002 NETS sample and column (3)-(4) uses the full sample from 1990 to 2007. Standard errors are clustered at the firm level. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

5.2 Step II

The goal of the second-step estimation is to back out the scale parameters of location-specific Frećhet distributions that represent the locations' state of technology T_s. By appealing to the calibrated value of θ and Equation (27) which draws on the model structure, I construct "purified" location-specific fixed effects that are purged of wage components as $\tilde{\xi}_{st} \equiv \hat{\xi}_{st} + (\theta + 1) \log w_s = \theta \log(T_s) + \phi \log \overline{MA}_s$, where w_s is the education-adjusted average weekly wage for the manufacturing sector.[17] Column (1) in Table 7 reports the purified fixed effect for each census division in 2002. Pacific division has the largest value which incorporates the location's state of technology and market access; East South Central division has the lowest one. These purified fixed effects depend on the value of θ which is calibrated to 3.6 in the baseline model, but I show shortly that the implied locations' state of technology are highly correlated when we vary the value of θ.

To estimate the coefficient on market access (ϕ), I follow the convention in the international trade literature by approximating the location-specific state of technology T_s by local R&D stock, and regress the purified location-specific fixed effects ($\tilde{\xi}_{st}$) on the logarithm of local R&D stock ($\log \text{R\&D}_{st}$), the logarithm of local market access ($\log \overline{MA}_{st}$) defined in

[17] Education-adjusted wage is calculated by $w_{st}^{\text{adj}} = w_{st} \exp(\mu H_{st})$, where H_{st} is the average year of schooling for location s at year t, and μ is the return to schooling that is set to 0.06 following Bils and Klenow (2000).

Equation (25), and census division fixed effects (δ_s):[18]

$$\tilde{\xi}_{st} = b_0 + b_{RD}\log(\text{R\&D}_{st}) + \phi \log \overline{MA}_{st} + \delta_s + u_{st}. \tag{28}$$

Table 6 shows the estimated coefficients. Column (1) and (2) control for the location's R&D stocks and market access, respectively. As the baseline specification, in column (3) I control for both terms. Consistent with the premise the location's appeal increases in both the location's productivity (proxied by local R&D stocks) and market access, the coefficients on both terms are positive and statistically significant. In particular, the elasticity with respect to market access (i.e., $\hat{\phi}$) is estimated to be 0.84. Then, I construct the state of technology for each census division by $\log(T_s) = (\tilde{\xi}_s - \hat{\phi}\log\overline{MA}_s)/\theta$. Table 7 reports the implied state of technology. Column (2) shows the baseline estimates with θ calibrate to 3.6. The state of technology differs from the location fixed effect because of the market access. For instance, compared to New England division, Middle Atlantic has a relatively higher local fixed effect but a lower state technology, indicating that it is mostly better market access that drives up Middle Atlantic's appeal. Lastly, column (3)–(5) vary the value of θ. As we increase the value of θ, there is still quite variations in the state of technology across locations and those estimates are highly correlated with the baseline ones with θ calibrated to 3.6.

Table 6: Second-Step Regression Results

	Estimated Fixed Effects of Census Divisions		
	(1)	(2)	(3)
Log(R&D stock)	1.155***		1.131***
	(0.041)		(0.042)
Log(Market access)		3.895***	0.843**
		(0.963)	(0.366)
N	162	162	162
R^2	0.925	0.422	0.928

Notes: The dependent variable variable is the census division fixed effects estimated in the first stage. Census division fixed effects are included in all specifications. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

[18] I construct local R&D stock by perpetual inventory method using industrial R&D expenditure. State-level R&D expenditure data are from Survey of Industrial Research and Development available from the National Science Foundation website. Before 1998, the R&D expenditure data were published only for odd years so I interpolate data by averaging the year before and after. For instance, $\text{R\&D}^{\text{exp}}_{1990} = (\text{R\&D}^{\text{exp}}_{1989} + \text{R\&D}^{\text{exp}}_{1991})/2$. Then, I calculate the R&D stock by $\text{R\&D}^{\text{stock}}_t = (1 - \delta_{\text{R\&D}})\text{R\&D}^{\text{stock}}_{t-1} + \text{R\&D}^{\text{exp}}_t$, where I assume the depreciation rate to be 0.15.

Table 7: Estimates of State of Technology

	Census Division FE	State of Technology			
		$\theta = 3.6$	$\theta = 2.5$	$\theta = 8$	$\theta = 12$
	(1)	(2)	(3)	(4)	(5)
New England	0.00	1.00	1.00	1.00	1.00
Middle Atlantic	0.37	0.96	0.99	0.92	0.91
East North Central	0.74	1.01	1.08	0.92	0.90
West North Central	-0.54	0.77	0.77	0.76	0.76
South Atlantic	0.35	0.85	0.90	0.78	0.76
East South Central	-0.86	0.79	0.80	0.77	0.76
West South Central	0.24	0.93	0.97	0.89	0.88
Mountain	-0.38	0.88	0.89	0.87	0.87
Pacific	1.12	1.16	1.26	1.05	1.02

Notes: Column (1) shows the census division fixed effects estimated in the first stage.Column (2)–(5) reports the state of technology constructed in the second stage for different values of local productivity dispersion. The state of technology of New England is normalized to one.

5.3 Step III

In the last step of estimation, I estimate the mean and dispersion of fixed costs of setting up establishments $(\beta_1^X, \beta_2^X, \sigma^X)$, firm-specific communication cost associated with low ICT level $(\underline{h})$, and the mean and dispersion of fixed cost of adopting ICT $(\mu^{ICT}, \sigma^{ICT})$ using simulated method of moments.

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

$$g(\phi) = [m - \hat{m}(\phi)]' W [m - \hat{m}(\phi)], \tag{29}$$

where W is the weighting matrix based on the covariance matrix of data moments.[19]

Simulation. I simulate 10,000 firms for each location that is considered as the headquarter location of the firm. Each firm draws a vector of 11 independent random variables. First, each firm independently draws a productivity z from lognormal distribution with mean μ^z and dispersion σ^z. Second, the firm also draws a vector of 9 independent standard normal random variables. Given the firm's headquarter location o, I transform those random variables to the fixed costs of setting up establishments f_{os}^X in each location s. The fixed costs of headquarter, i.e., f_{oo}^X is set to zero. Lastly, the firm draws a fixed cost of ICT adoption from lognormal distribution with mean μ^{ICT} and dispersion σ^{ICT}.

[19] The variance-covariance matrix is obtained by 100 bootstrapped samples.

Moments and identification. I use three sets of moments constructed from the matched HH-NETS data.The first set regards firm expansion patterns that include the overall share of multi-unit firms, the share of multi-unit firms with employment below median, and the share of firms headquartered at o and have establishment in $s \neq o$, where $o, s = \{1, 2, \cdots, 9\}$. In total, there are 74 moments associated with firm expansion patterns. These moments are informative of the fixed costs of setting up establishments. In particular, the overall share of multi-unit firms decreases in the average fixed costs, and thus helps identify the mean of the fixed costs. Variations in the shares of multi-unit firms for each headquarter-establishment pair help identify the role of distance in fixed costs. The share of multi-unit firms with employment below median is informative of the dispersion of the fixed costs. The idea is that only the most productive firms, which are also the largest firms, would become multi-unit firms if there is no dispersion. As the fixed costs become more dispersed, firms with low productivity may draw small fixed costs, allowing them to expand. The second set of moments regards firms ICT adoption including the overall share of firms adopted Intranet and the share of adopting firms with employment below median. Similarly, these moments help pin down the mean and dispersion of the fixed costs of ICT adoption, respectively. Lastly, the third set of moments include the correlation between firm expansion and ICT adoption, i.e., Corr(Intranet,multi-unit). Along with the share of firms adoption ICT, the correlation helps identify the firm-specific communication cost associated with low ICT. The larger the communication cost, the higher the correlation and the larger the share of firms adopting ICT.

Estimation results. Table 8 reports the estimates in the third-step estimation. The fixed costs of setting up establishments (f^X_{os}) increase in the distance between the headquarter and the establishment, with an elasticity of 0.15. In terms of magnitude, the average fixed costs paid conditional on firms setting up additional establishments are \$1.7–\$4.4 million in 2002 US dollars. Pacific division is estimated to have the highest fixed costs with an average around \$3.5 million. The estimates are lowest in West North Central division at around \$1.9 million.[20] Through the lens of the model, the fixed costs paid by multi-unit firms are about 24.7% of the firms' 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.

The firm-specific communication cost associated with low ICT ($\underline{h}$) is estimated to be 1.268. As the cost associated with high ICT is normalized to 1, the estimated $\underline{\tilde{h}}$ can be

[20]Table 9 reports the conditional average fixed costs paid in each census division. I calculate the costs by assuming the ratio of average sales to the fixed costs from the model is the same as that in data.

translated into a 23.7%($= \log 1.268 - \log 1$) increase in the firm-wide communication cost. We can also interpret the estimate in terms of efficiency loss in firm's *effective* productivity, i.e., $\tilde{z} = z/h(\varphi)$. A firm with low ICT level experiences a 23.7% productivity disruption compared to its counterpart with high ICT level.

The estimated fixed costs of ICT adoption (f^{ICT}) is relatively smaller than that of setting up establishments (f^X). The average fixed costs paid by firms that adopt high ICT level is $158,000 in 2002 US dollars, which is around 3.8% of the firms' total profits. The value of fixed costs of ICT adoption could include not only the actual monetary costs paid for hardwares and softwares to set up the Intranet, but also the value of time to upgrade the system measured as forgone profits. There is larger dispersion in the fixed cost of ICT adoption. This is because many small and single-unit firms also adopt Intranet in data.

Table 8: Parameter Estimates

	β_1^X	β_2^X	σ^X	$\underline{\tilde{\varphi}}$	μ^{ICT}	σ^{ICT}	log(Loss Function)
Estimate	1.894	0.245	1.881	1.268	0.134	16.494	918.390
S.E.	(0.061)	(0.007)	(0.035)	(0.034)	(0.008)	(1.554)	

Notes: This table reports the estimates from the third step estimation and corresponding loss function. Standard errors are obtained from bootstrap.

Table 9: Average Fixed Cost f^X Conditional on Having an Establishment

Census Division	Average f^X
New England	$2.19 mil.
Middle Atlantic	$2.77 mil.
East North Central	$2.17 mil.
West North Central	$1.95 mil.
South Atlantic	$2.82 mil.
East South Central	$2.39 mil.
West South Central	$2.94 mil.
Mountain	$2.43 mil.
Pacific	$3.52 mil.

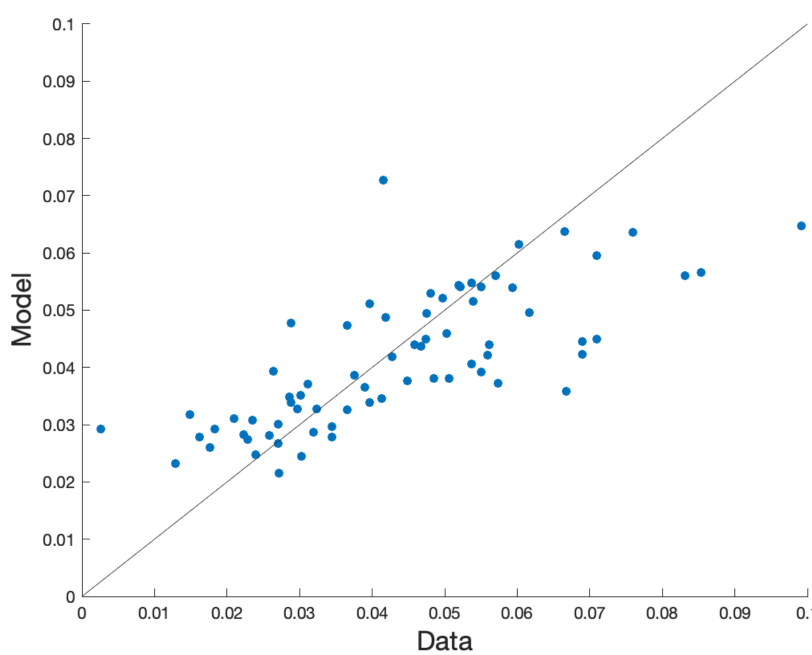
Notes: This table reports the estimated monetary average value for the fixed costs of setting up establishments in each census division.

Model fit. For brevity, I show the model fit of bilateral expansion patterns in Figure 5 and report the other moments in Table 10. The first column in Table 10 shows the data moments, and the second column shows the simulated moments through the model. The model fits the data reasonably well. The share of firms adopting Intranet is 44.8% in data and is 45.0%

in model simulation. The correlation between Intranet adoption and geographic expansion is also matched well – 0.14 in data and 0.15 in model.

The overall share of firms with establishments in multiple divisions is 19.4% in data and is 16.8% in model simulation. While the model generates 0.1% of firms with multiple establishments that are below median employment, the share is somewhat smaller than the 2.2% in data. Figure 5 plots the simulated share of multi-unit firms for each headquarter-establishment pair against those in data. The scatter plots lie along the 45-degree line, with a correlation of 0.76. It is worthwhile noting that the bilateral expansion shares are not only affected by the fixed costs of setting up establishments that are estimated in the third step, but also affected by the location-specific technology states, i.e., T_s, which are estimated in the second step using within-firm variations in employment shares. That said, the location-specific fixed costs estimated in the last step helps improve the matching.

Figure 5: Model Fit: Bilateral Expansion Patterns



Notes: This figure plots the model simulated shares of firms that expand from one census division to another against those shares in data.

6 Counterfactuals

In this section, I use the parameters estimated in the previous section to conduct counterfactual analysis. First, I show that firms' multi-unit production is crucial for evaluating the

Table 10: Model Fit

	Data	Model
Share of multi-unit firms	0.194	0.168
with employment below median	0.022	0.001
Share of firms adopting Intranet	0.447	0.450
with employment below median	0.196	0.176
Corr(Intranet,multi-unit)	0.144	0.150

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

gains from ICT, as the multi-unit firm is an additional channel for technology spillover across space. A model absent multi-unit production tend to underestimate the gains from ICT. The model also allows me to shed light on the general equilibrium effects of the Internet Privatization in addition to the reduced-form estimates in Section 3. Through the lens of the model, I find that the reform reduced the manufacturing price by 1.76%, on average. The East South Central division witnessed the largest benefits while the Pacific division saw the least. Lastly, I simulate a reduction the bilateral communication cost between the Pacific and WSC divisions and highlight the importance of the interdependency of firms' location choices.

Throughout the counterfactuals, I treat the total GDPs and wages fixed so the welfare changes are captured by changes in the manufacturing prices.

6.1 Gains from ICT Accessibility

Since the early invention in the late twentieth century, ICT applications such as Intranet have experienced rapid development and have been gradually accessible to all businesses during the last decade. What are the gains from ICT accessibility? In this section, I measure the gains from ICT accessibility by the proportional changes in the locations' manufacturing price indexes P_s as we move away from the counterfactual equilibrium where ICT is unavailable, i.e., the fixed cost of ICT $f^{ICT} \to \infty$. I consider both the gains from local ICT accessibility that mirrors the early stage of technology diffusion, and the gains from universal accessibility that mirrors the later stage where one technology is accessible to all locations and firms.

6.1.1 Local ICT accessibility

As California has been considered as one center for ICT developments, I first assess the gains from local ICT accessibility in the Pacific division. Particularly, I reduce the fixed cost of

ICT from infinity to the benchmark estimate in the Pacific division while keeping the cost infinite in the rest of the locations. The reduction in the ICT cost induces 46.3% of firms from the Pacific to adopt the technology to reduce communication costs. Accompanied with this technology upgrading, the fraction of multi-unit firms in the Pacific increases by 2.9 percentage points, which is a 20% increase relative to the fraction when ICT is unavailable. This increase in multi-unit firms from the Pacific underscores the complementarity between technology upgrading and geographic expansion. All the other locations see increasing numbers of establishments set up by the Pacific firms but to different degrees. Panel (A) in Figure 6 shows the percent changes in the share of Pacific firms that set up establishments in each location, compared to that when ICT is unavailable. For instance, the share of Pacific firms that set up establishments in the New England division increases by 32% from 2.2 to 2.9 percentage points. Locations seeing the largest increase in the Pacific establishments are those locations with high productivity and large relative fixed cost of setting up establishments for the Pacific firms, e.g., the New England and the East North Central divisions. As ICT becomes available, the Pacific firms have the option of ICT upgrading and thus increase their effective productivity, which allows them to set up establishments in the locations that were out of their reach. Locations—such as the Mountain division—that the Pacific firms have already entered when ICT is unavailable, on the other hand, see less relative changes in the expansion patterns. While the Pacific firms are able to increase their geographic footprints, firms in other locations experience contraction due to the general equilibrium effects as the markets become more competitive.

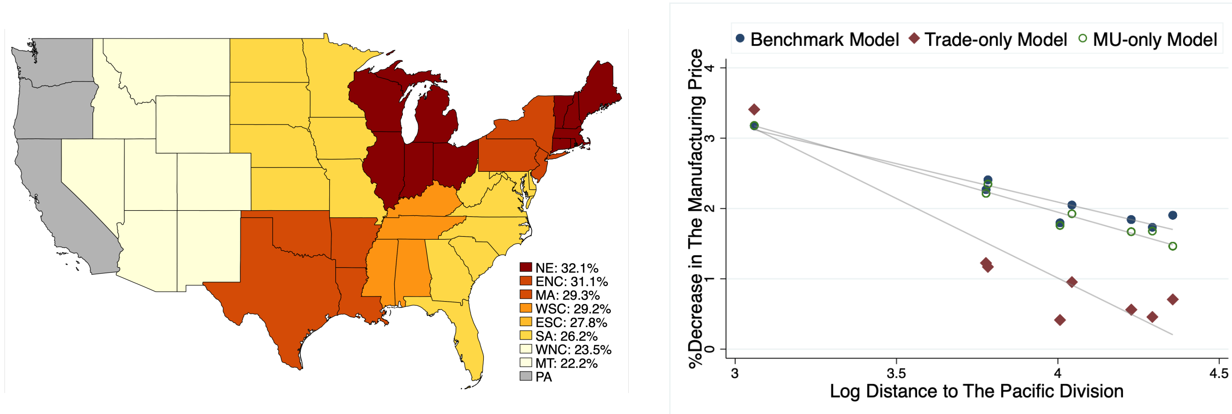
Table 11 reports the changes in the manufacturing prices that capture the welfare effects associated with Pacific ICT accessibility. The larger reduction in the manufacturing price, the larger the gains from ICT accessibility. Column (1) shows the results from the benchmark model. Unsurprisingly, the Pacific division benefits most with a 6.14% drop in the manufacturing price, but it is noteworthy that other locations also benefit from this regional technology development taking place in the Pacific division. In non-Pacific locations, the manufacturing prices decrease by 2.02%, on average, which is around one-third of the decrease in the Pacific.[21] The lower panel of Table 11 reports the price change in each location, ranging from -3.18% decrease in the Mountain division to -1.73% in the Middle Atlantic division.

Through the lens of the model, non-Pacific locations benefit from this local technology improvement via two channels—trade and multi-unit production. To disentangle these two channels, I compare the gains from ICT in the benchmark model with alternative models

[21] The manufacturing price in non-Pacific locations is calculated by the average price of the other locations weighted by corresponding output.

Figure 6: ICT Accessibility In The Pacific Division

(A) %Changes In Expansion Pattern of Pacific Firms (B) %Changes in Manufacturing Price



Notes: These figures show the changes in the expansion patterns and efficiency gains, by allowing firms in the Pacific census division to access ICT. In particular, the fixed cost of adopting ICT is reduced from infinity to the baseline estimate for the Pacific firms. Panel A shows the percentage changes in the share of firms that are headquartered at the Pacific census division and set up additional establishments in other census divisions. Panel B plots the percentage changes in the manufacturing price index for each census division against its distance to the Pacific division.

that shut down each channel respectively. Column (2) shuts down the multi-unit production so as to focus on the trade channel. The gains from ICT is limited to the Pacific division: Compared to the 12.86% price drop in the Pacific, non-Pacific locations see a much smaller price decrease by 0.82% which is less than one-ten of that in the Pacific.[22] Furthermore, the gains are geographically concentrated to those locations that are closer to the Pacific and decay rapidly in the distance. The division that is closest to the Pacific—the Mountain division—sees a 3.41% manufacturing price decrease, which is comparable to that in the benchmark model. On the other hand, far-away locations such as the New England division see as little change as 0.71% decrease in the price. Column (3) shuts down the trade and focus on the channel of multi-unit production. The price drops are slightly smaller than those in the benchmark model, but are more widely spread compared to the model without multi-unit production. Panel (B) in Figure 6 plots the percentage change in the manufacturing price (in absolute value) of each location against the logarithm of its distance to the Pacific. The benchmark model and the MU-only model predict the price reductions that are decreasing at a lower speed in the distance. Compared to the trade-only model, the models with multi-

[22]Decrease in the manufacturing price in the Pacific is driven by increase in the effective productivity of local establishments that adopt ICT. Those establishments constitute a larger share of total number of establishments in a trade-only model, thus leading to a larger increase in the manufacturing price. In the benchmark model with multi-unit production, local establishments share a smaller fraction because non-Pacific firms also set up establishments in the Pacific. As a result, ICT upgrading of the local firms lead to a smaller increase in the average productivity in the Pacific and thus a smaller decrease in the price index.

Table 11: ICT Accessibility in The Pacific Division

Census Division	%Change in Manufacturing Price			
	Benchmark (1)	Trade-Only (2)	MU-Only (3)	Fixed Locations (4)
Pacific	-6.14	-12.86	-6.47	-6.84
Non-Pacific	-2.02	-0.82	-1.92	-1.86
New England	-1.90	-0.71	-1.46	-1.71
Middle Atlantic	-1.73	-0.46	-1.68	-1.58
East North Central	-1.80	-0.41	-1.76	-1.60
West North Central	-2.27	-1.22	-2.22	-2.15
South Atlantic	-1.84	-0.56	-1.67	-1.69
East South Central	-2.05	-0.95	-1.93	-1.93
West South Central	-2.41	-1.17	-2.35	-2.17
Mountain	-3.18	-3.41	-3.18	-3.20

Notes: This table compares the changes in efficiency gains from different models, by allowing firms in the Pacific census division to access ICT. In particular, the fixed cost of adopting ICT is reduced from infinity to the baseline estimate for the Pacific firms. Column (1)–(3) report the percentage changes in manufacturing price indices in the benchmark model, a trade-only model, and a multi-unit production model. Column (4) fixed the firms' location choices to those in the benchmark model when ICT is unavailable.

unit production yield gains from ICT that are more geographically dispersed, highlighting its role in technological spillover across space.

Finally, I break down the role of multi-unit production in transmitting local technology enhancements. The technology spills over to other locations via multi-unit production through three channels. First, all establishments—including those in other locations—of the Pacific firms experience productivity increase for those firms adopting ICT. This direct spillover effect reduces the price indexes in other locations. Second, because of the complementarity between ICT upgrading and geographic expansion, the Pacific firms set up more establishments in other locations, which further enhance the positive spillover effect to other locations. Third, the general equilibrium effect due to more competitive markets pushes the firms in other locations to contract, thus leading to price increases. To illustrate the role of geographic expansion (and contraction) on the distribution of gains from ICT, I compare the benchmark model with the one fixing the firms' locations choices to the same locations as those when ICT is unavailable. Column (4) shows that around 90%$(= 1.86/2.02 \times 100)$ of the gains in non-Pacific locations come from the productivity increase of the current establishments. Put differently, the geographical expansion of Pacific firms contribute to around 10% of the gains. This relatively small contribution from the geographic expansion is not contradictory to the significant increase in the fraction of multi-unit firms in the Pacific division. While the Pacific firms witness a notable geographic expansion as showed in Panel (A) of Figure 6, the newly expanded firms are, on average, less productive than those incumbent multi-unit firms and thus have less impacts on the price indexes in other locations.

6.1.2 Universal ICT Accessibility

Now I consider the gains from universal ICT accessibility by setting the fixed cost of ICT to the benchmark estimate for all firms. Column (1) in Table 12 shows that the benchmark model predicts a decrease in the average manufacturing price by 14.59%. As firms in all locations have access to ICT and the distribution of ICT cost is the same in every location, the fraction of firms adopting ICT is also similar across locations. This leads to a similar change in the distribution of firms' effective productivity, and thus the change in the price indexes. Column (2)–(4) report the results for the trade-only model, multi-unit-production-only model and the benchmark model with fixed locations, respectively. The magnitude of price reduction is somewhat similar using alternative models, which is driven by the productivity increase of local establishments. That said, as showed in column (2), the trade-only model tends to underestimate the gains from ICT. With multi-unit production, all establishments—including those in other locations—would see productivity improvements for firms adopting ICT which are the most productive firms on average.

There is a growing literature that draws attention to the difference between national versus local market concentration. While national concentration is increasing, evidences on local concentration are inconclusive. As the majority of top firms in the US have more than one establishment, it is essential to take multi-unit production into account. Appendix Table 19 reports the sales shares of the top 1%, 10% and 20% establishments, respectively, at both the national and local levels. Column (1)–(3) reports the results for the benchmark model, and column (4)–(6) for the trade-only model. The benchmark model with multi-unit production is able to generate a disparity between the local and national concentration—in particular, a relatively low concentration at the local level but a high level at the national level. This is because more productive firms can set up additional establishments in other locations to lower input cost and take advantage of low trade costs to the destination markets. On the other hand, the trade-only model generates the same local concentration as the national one. Panel B shows that universal ICT accessibility leads to an increase in the national concentration, but have ambiguous impacts on local concentrations especially regarding the top 1% establishments. For instance, the New England division sees an increase in the sales share of the top 1% establishments by 6 percent; The West South Central and the Mountain division instead see decreases in sales shares of the top 1% establishments by 1 percent. In

Table 12: ICT Accessibility in The Pacific Division

Census Division	%Change in Manufacturing Price			
	Benchmark (1)	Trade-Only (2)	MU-Only (3)	Fixed Locations (4)
National Average	-14.59	-14.22	-14.69	-14.35
New England	-14.66	-14.15	-14.37	-14.50
Middle Atlantic	-14.65	-14.21	-14.61	-14.44
East North Central	-14.51	-14.21	-14.52	-14.46
West North Central	-14.83	-14.17	-15.08	-14.72
South Atlantic	-14.45	-14.25	-14.81	-14.19
East South Central	-14.74	-14.20	-14.85	-14.53
West South Central	-14.65	-14.24	-14.70	-14.37
Mountain	-14.65	-14.21	-14.14	-14.47
Pacific	-14.58	-14.26	-14.83	-14.03

Notes: This table compares the changes in efficiency gains from different models, by allowing all firms to access ICT. In particular, the fixed cost of adopting ICT is reduced from infinity to the baseline estimate for all firms. Column (1)–(3) report the percentage changes in manufacturing price indices in the benchmark model, a trade-only model, and a multi-unit production model. Column (4) fixed the firms' location choices to those in the benchmark model when ICT is unavailable.

contrast, a trade-only model generates the same increase in the local concentration for every location as that at the national level, even thought the trade-only model. That said, the sales share of top 10% establishments increases for every location: More productive firms are able to adopt ICT to further enhance effective productivity, thus capturing a larger market share.

6.2 The Internet Privatization

By difference-in-difference regressions, Section 3 finds that the Internet privatization increased the fraction of multi-unit firms and the average number of units per firm by 3.19% and 1.11%, respectively. While the reduced-form estimates are useful to learn partial equilibrium effects of the privatization on firms' geographic expansion, what are the effects in a general equilibrium where prices of manufacturing goods adjust endogenously? In this section, I use the calibrated model to shed light on the general equilibrium effects of the Internet privatization. In particular, I reduce the cost of ICT adoption, i.e., f^{ICT}, to mimic the Internet privatization.[23] As the model is calibrated to the post-privatization economy,

[23] Through the lens of the model, the Internet privatization could reduce the multi-unit production disruption by reducing the fixed cost of ICT and thus reduces firm-specific communication cost $h(\varphi)$; or by

I first back out the change in the average fixed cost of ICT (i.e., $\mu^{ICT}_{\text{pre-privatization}}$) using the partial equilibrium model, fixing equilibrium prices to those in the post-privatization equilibrium, so that the changes in the fraction of multi-unit firms and average number of units per firm match the reduced-form estimates. Then, I use $\mu^{ICT}_{\text{pre-privatization}}$ to simulate the general equilibrium counterfactual.

One concern is that the reduced-form coefficients not only reflect the partial equilibrium effects but also general equilibrium ones, as the Internet privatization might have affected regional ideal price indexes. Fortunately, this concern is addressed by the state-year fixed effects which would absorb any variations in the firm span of control that come from regional prices and other factors. The key is that my identification comes from variations at the ZIP code level, while the ideal price indexes are determined at a larger regional level, e.g., census divisions.[24]

Table 13 compares the reduced-form estimates, model-simulated partial equilibrium effects, and general equilibrium effects, respectively. Column (1) reports the estimated changes (%) from the reduced-form analysis. Column (2) reports the changes in partial equilibrium when I reduce the average fixed cost of ICT from 4.5 to the baseline estimate (i.e., $\mu^{ICT} = 0.1339$). Decrease in the fixed cost of ICT directly leads to an increase in the fraction of firms adopting ICT by 29.26%. Due to the complementarity between ICT adoption and geographic expansion, we also see increase in multi-unit production. The changes at both the extensive and intensive margins match well with the reduced-form estimates. Finally, the last column shows the general equilibrium results allowing manufacturing prices to adjust endogenously. As the reduction in fixed cost of ICT is the same, ICT adoption rate is similar. The geographic expansion, however, is smaller: The fraction of multi-unit firms and the average number of units per firm increases by 0.72% and 0.18%, respectively, which is around one-fifth of the magnitude when aggregate prices are fixed. This is because as markets become more competitive, some multi-unit firms at the margin contract or even become single-unit firms. Regarding the welfare gains, Appendix Table 20 shows in more detail the price change for each location. Particularly, the manufacturing price increased the most in the East South Central division but the least in the Pacific division. On average, through the lens of the benchmark model, the Internet Privatization reduces the national average manufacturing price by 1.76%.

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reducing the exogenous bilateral communication cost $d_{os} = \exp(\beta^d \log \text{Miles}_{os})$ which is increasing in the distance between the two locations. In the first-step estimation, I use within-firm employment shares to estimate the coefficient on the distance, β^d, for the exogenous term in each year. The coefficient is consistently estimated around 0.25, indicating that the slope of communication cost as a function of distance is stable over time.

[24] Appendix section E.2 shows in more details that general equilibrium effects that are mediated from larger regional level, such as the census division level, are absorbed by region-year fixed effects.

Table 13: Related to Reduced-Form Analysis

%Change in	Reduced-Form (1)	Model: Partial Equilibrium (2)	Model: General Equilibrium (3)
Fraction of firms adopting ICT	–	29.26	28.87
Average number of units per firm	1.11	1.10	0.18
National Avg. Manufacturing Price	–	–	-1.76

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

6.3 Improve Communication Infrastructure

Communication infrastructure may experience unequal development and have differential impacts across locations. In this section, I conduct a counterfactual that mimics improvements in the communication infrastructure, such as direct flights and broadband, between two divisions—the Pacific and West South Central divisions. In particular, I reduce the exogenous communication cost between the two locations, i.e., $d_{\text{Pacific,WSC}}$ and $d_{\text{WSC,Pacific}}$, by 20%. The benchmark model predicts unequal benefits to the two locations with the same cost reduction. In addition, I compare the benchmark model with the multi-unit-production-only model to highlight the interdependency of locations choice.

Table 14 reports the changes in the expansion patterns. For instance, the first row shows the percent changes in the fraction of firms from the Pacific division that set up establishments in the West South Central and other divisions, respectively. As the communication cost decreases between the two divisions, the share of Pacific firms expanding to the WSC division increases by 58.5%. Since the production locations are substitutes to each other, this expansion to the WSC is companied with a reduction of expansion to other regions by 1.1%. The WSC firms also relocate part of the productions from other divisions to the Pacific division, following a reduction in the communication cost. The establishments of firms from other divisions, however, were crowded out from the Pacific and WSC divisions. Lastly, firms from other divisions experience contraction in other locations as well due to the increasing competitiveness of the markets.

The relocation from other divisions emphasizes the importance of interdependency of location choices by incorporating both multi-unit production and trade into account. In a model without trade but only multi-unit production, establishment location choice is independent given the prices. As showed in column (6), the MU-only model does not generate

Table 14: Reduce Exogenous Communication Cost Between The Pacific and The WSC
Changes in Expansion Patterns

	Benchmark Model			MU-Only Model		
%Changes in Fraction of Firms	Pacific (1)	WSC (2)	Other Divisions (3)	Pacific (4)	WSC (5)	Other Divisions (6)
Pacific	-	58.4	-1.1	-	49.2	0.0
WSC	46.1	-	-1.0	43.2	-	0.0
Other Divisions	-3.8	-5.5	-0.5	-3.3	-7.8	0.0

Notes: This table shows the percentage changes in the expansion patterns following a 20% reduction in the exogenous communication cost between the Pacific and West South Central (WSC) census divisions. Column (1)–(3) report the results in the benchmark model. Column (4)–(6) report the results in a multi-unit production only model.

contraction in other locations.

Table 15 shows the change in the manufacturing price for each location. Column (1) reports the results from the benchmark model. While the bilateral communication costs decrease to the same extent for the Pacific and WSC divisions, the WSC division experiences a larger price reduction than the Pacific division. The manufacturing price decreases by 3% reduction in the WSC, compared to the 1.9% reduction in the Pacific.

In column (2), I fix the firms' location choices to the ones as the benchmark equilibrium. It is noteworthy that productivity improvements of the existing establishments account for the majority of the price reduction. With establishments locations fixed, the WSC already sees a larger benefit than the Pacific. This is because that the establishments in the WSC set up by the Pacific firms, however, are more productive on average compared to the establishments in the Pacific that are set up by the WSC firms. As a result, following a reduction in the communication cost, the establishments in the WSC by Pacific firms have a larger increase in the productivity, on average, which leads to a larger benefit to the WSC. Firms' endogenous relocation further widens the benefit difference between the WSC and Pacific: As showed in Table 14, more Pacific firms set up establishments in the WSC than the other direction. Other locations also witness decreases in the prices through trade. Locations that are closer to the Pacific and WSC, such as the Mountain division, benefit to a larger extent than the remote locations. Column (3) shows the results by the MU-only model. In line with the expansion pattern in column (6) of Table 14, the price reduction is local to the two locations experiencing cost reductions. The manufacturing prices remain the same for the rest of the locations.

Table 15: Reduce Exogenous Communication Cost Between The Pacific and The WSC Changes in Manufacturing Prices

Census Division	%Change in Manufacturing Price		
	Benchmark (1)	Fixed Locations (2)	MU-only (3)
National Average	-0.7	-0.6	-0.7
New England	-0.1	-0.1	0.0
Middle Atlantic	-0.1	-0.1	0.0
East North Central	-0.1	-0.1	0.0
West North Central	-0.3	-0.3	0.0
South Atlantic	-0.1	-0.1	0.0
East South Central	-0.2	-0.2	0.0
West South Central	-3.0	-2.4	-3.5
Mountain	-0.3	-0.3	0.0
Pacific	-1.9	-1.6	-1.7

Notes: This table compares the efficiency gains from different models following a 20% reduction in the exogenous communication cost between the Pacific and West South Central (WSC) census divisions. Column (1) reports the percentage changes in manufacturing price indices in the benchmark model for each census division. Column (2) fixes firms' location choices to those in the baseline equilibrium. Column (3) reports the price changes in a multi-unit production only model with endogenous location coices.

7 Conclusion

Recent development in Information and communication technologies (ICT) has widened firms' geographic span of control, allowing them to expand production across locations. This paper provides empirical evidence and studies the efficiency gains from this technology improvement through firm geographic expansion.

First, I exploit a large comprehensive dataset with establishment-level ownership linkages and geographic locations, and further augment it with a database of establishment ICT usage. I document that firms in the US manufacturing sector have increased their geographic span of control, especially those with multiple production sites; and that firms with advanced ICT software are associated with a larger geographic span of control. Going beyond a simple correlation, I show empirically that ICT improvements help widen firms' geographic span of control by exploiting quasi-experimental variation from a historical event in the history of US Internet development: the Internet privatization in 1995. Using a difference-in-indifference approach, I find that the privatization in 1995 can explain 38% of the total increase in the firm geographic span of control, e.g., the average number of counties per firm, during 1996-2007.

Guided by these empirical findings, the paper proposes and estimates a model of firm ICT adoption and geographic expansion. Firms choose a set of locations, instead of a single location, to set up establishments but are subject to communication costs among establishments. Firms can adopt advanced ICT to reduce communication costs and thus increase firm-specific effective productivity for all establishments. Finally, I use the model to shed light on the distributional and aggregate efficiency gains. Compared to an alternative trade-only model, gains from ICT improvements are larger when we take the multi-unit production into account. Importantly, multi-unit firms work as a channel for technology spillover across space. As a result, my model predicts that gains from local ICT improvements are also more geographically dispersed. I use the model to study the efficiency gains from the Internet privatization: on average, the privatization reduced the manufacturing price index by 1.76%; states in the East South Central census division witnessed the largest benefits, while those in the Pacific saw the least. Lastly, I conduct policy counterfactuals, highlighting that gains from ICT improvements differ across geographic locations, and that multi-unit firm production patterns help explain these differences.

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Appendix

A Data

A.1 Match Harte-Hanks with National Establishment Time Series

I match establishments in the two datasets by *company name* and *address*. Among 91129 observations in the 2002 Harte-Hanks dataset, 47275 of them (51.9%) are matched with the NETS manufacturing package. The manufacturing sector has a higher matching rate of 83.1%. Among matched establishments, around 40% are matched by company name, and 60% are matched by address. In particular, I checked company names for those that are matched by addresses.

Most cases appear to be reasonable. For instance, an establishment with company name "InMetal Inc" in HH is matched with "INDUSTRIAL METAL PDTS CO INC" in the NETS by address. Another example is that an establishment named as "Arthur Blank & Company Inc" in the HH is under the name "ABNOTE USA INC" in the NETS, but the addresses are the same in the two datasets – "225 Rivermoor St, Boston". It turns out that ABnote Group acquired Arthur Blank & Company Inc in 2007.

There are also some cases that establishments share the same address but are under different company names. For instance, the address "1 Jericho Plz" linked two companies – "Schonfeld Securities L L C" in the HH and "C M P MEDIA LLC" in the NETS. Yet the overall impression is that those cases appear infrequently.

Table 16: Comparison of Matched and Unmatched Establishments in 2002 Harte-Hanks Database

	Manufacturing			All Sectors		
	Matched	Unmatched	Total	Matched	Unmatched	Total
Employment	371.0	303.1	359.6	400.3	335.7	369.2
	(2376.0)	(541.0)	(2178.3)	(4853.0)	(2033.9)	(3769.5)
Revenue	89.7	72.4	86.8	92.70	66.26	79.98
	(729.9)	(226.4)	(672.1)	(644.7)	(568.2)	(609.2)
# Observations	4826	23844	28670	43854	47275	91129

B National Science Foundation Network (NSFNET)

This appendix section introduces a brief history of the National Science Foundation Networks from its initiation in 1986 to the final privatization in 1995.

1986-1991: Expansion and Upgrade

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

During the first two years after its operation, the NSFNET experienced the first round of upgrade and expansion. The network was expanded to thirteen nodes, where the seven new nodes were located in Salt Lake City, Utah; Palo Alto, California; Seattle, Washington; Lincoln, Nebraska; Houston, Texas; Ann Arbor, Michigan; and College Park, Maryland. The speed increased to 1.5 Mbit per second (so-called T-1 network).[25] Moreover, the NSFNET provided connection to these backbone nodes from regional networks; these regional networks were in turn connected to smaller regional and campus networks.

Since 1990, the NSFNET started its second round of upgrade and expansion. By the end of 1991, the network had added three more nodes in Atlanta, Georgia; Argonne National Laboratory in Lemont, Illinois; and Cambridge, Massachusetts. The speed increased to 45 Mbit per second (so-called T-3 network). The core backbone equipment were 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, the restriction was gradually lifted.

In March 1991, the *Acceptable Use Policy* was revised, allowing the NSFNET to carry commercial internet traffic. The Scientific and Advanced Technology Act of 1992 formally authorized the NSF "... to foster and support access by the research and education communities to computer networks which may be used substantially for additional purposes if this will tend to increase the networks' overall capabilities."[26] In the spring of 1993, the NSF released a solicitation to the private sector, transiting to a new Internet architecture; the

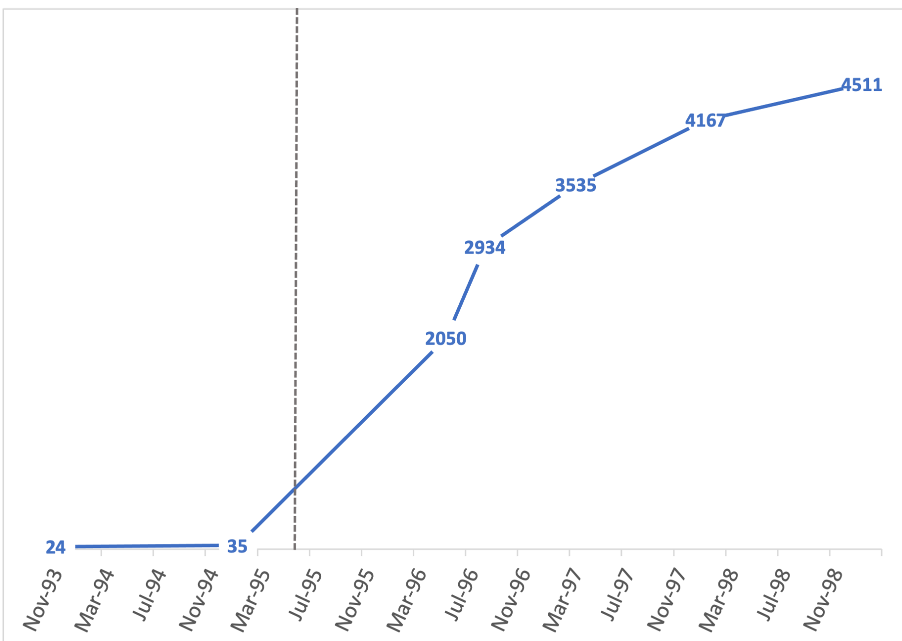
[25]The National Science Foundation (NSF) partnered with Merit Network, a consortium of Michigan universities, and industry players including IBM and MCI. In the upgrading and expanding process, IBM provided hardware and software support, and MCI provided fiber-optic circuits at a reduced rate.

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

awards were announced in 1994.[27]

While attempts to commercialize the Internet started since the early 1990s, "Internet gold rush" had not arrived until the last moment when the NSFNET backbone was decommissioned in April, 1995. Final restrictions on the commercial Internet were lifted. Together with business successes at the time, the privatization catalyzed explosive development of the Internet and related industries. Figure 7, adapted from Table 5.1 in Greenstein (2015), shows the number of Internet service providers that were listed in *Boardwatch Magazine* during 1993-1998.[28] The number slightly increased from 24 in November 1993 to 35 in January 1995, but jumped to over 2000 by May 1996, reflecting rapid developments of commercial Internet access that followed the Internet privatization.

Figure 7: Number of Internet Service Providers (ISP) 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).

Advanced Research Projects Agency Network (ARPANET)

The NSFNET was closely related to its predecessor, the Advanced Research Projects Agency Network (ARPANET) funded by Department of Defense since the 1960s. Following the

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

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

ARPANET, the NSFNET used packet-switching technology and the TCP/IP protocol.[29] The nodes' locations of the NSFNET were also influenced by those of the ARPANET whose nodes were mostly located at military bases, federal agencies and university's computer science departments. Therefore, the locations of the NSFNET nodes were less likely to be subject to contemporaneous local shocks.

C Additional Reduced-Form Tables

[29]In a packet-switching network, data delivered from a source device is broken into packets, and will be reassembled at the target device. The Transmission Control Protocol (TCP) and the Internet Protocol (IP) ensures that these packets reach the target device and are reassembled in the right order.

Table 17: Estimated Effects of Internet Privatization on Firm Expansion

	#Non-Drivable Counties		#Out-of-State Counties		Average HQ-EST Distance	
	(1)	(2)	(3)	(4)	(5)	(6)
DistToNode X Post	-0.026***	-0.020***	-0.031***	-0.024***	-0.011*	-0.008
	(0.006)	(0.006)	(0.006)	(0.007)	(0.006)	(0.006)
Log(Pop)		-0.088*		-0.083		0.066
		(0.048)		(0.054)		(0.057)
Log(Median Income)		-0.013		-0.040		0.285***
		(0.081)		(0.086)		(0.107)
%Bachelor		0.013***		0.016***		0.002
		(0.002)		(0.002)		(0.002)
%Black		0.004**		0.005**		0.003
		(0.002)		(0.002)		(0.002)
%Over65		0.004		0.003		0.005
		(0.003)		(0.004)		(0.005)
Observations	911034	911034	911034	911034	911034	911034
Clusters(firms)	50613	50613	50613	50613	50613	50613
Avg. Dep.	0.198	0.198	0.240	0.240	0.738	0.738
R^2	0.824	0.824	0.830	0.830	0.886	0.886
Industry-Year FE	Y	Y	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y	Y	Y

Notes: This table uses 1990-2007 NETS to estimate the difference-in-difference regressions of the form:

$$Y_{ist} = \alpha_i + \beta_t \text{DistToNode}_s + Z_{ct}\lambda + \delta_{jt} + \eta_{ft} + \varepsilon_{ist},$$

where the dependent variable is a measure of firm geographic span of control for firm i at location s in year t, and location is measured at the ZIP code level. α_i is firm fixed effect, DistToNode_s is the distance from location s to the nearest NSFNET node, Post_t is a dummy variable set to 1 for years since 1995, Z_{ct} is a vector of county-year characteristics, δ_{jt} is industry-year fixed effect, η_{ft} is state-year fixed effect, and ε_{ist} is the error term. The dependent variable for column (1)–(2) is the number of non-drivable counties; that is, counties located more than 250 miles away from the headquarter. The dependent variable is the number of out-of-state counties for column (3)–(4), and is the average distance from a firm's establishments to its headquarter, weighted by the establishment employment share within the firm, for column (5)–(6). Firm fixed effect, industry-year fixed effect and state-year fixed effects are included in all columns. Column (2), (4), and (6) control for additional county characteristics. Standard errors are clustered at the firm level.

Table 18: Estimated Effects of the Internet Privatization on Firm Expansion: Employment Weighted

	Number of Counties of All Firms		Number of Counties of MU Firms		MU Indicator	
	(1)	(2)	(3)	(4)	(5)	(6)
DistToNode X Post	-0.428***	-0.342***	-0.870**	-0.854**	0.003	0.004
	(0.104)	(0.110)	(0.380)	(0.414)	(0.006)	(0.005)
Log(Pop)		-0.428		0.347		0.050
		(0.889)		(2.830)		(0.040)
Log(Median Income)		-0.841		-0.657		0.169**
		(1.473)		(5.633)		(0.085)
%Bachelor		0.129***		0.044		-0.001
		(0.039)		(0.138)		(0.002)
%Black		0.041		0.015		0.000
		(0.038)		(0.103)		(0.001)
%Over65		0.054		0.272		0.001
		(0.073)		(0.212)		(0.004)
Observations	911034	911034	34308	34308	911034	911034
Clusters(firms)	50613	50613	1906	1906	50613	50613
Avg. Dep.	3.887	3.887	8.596	8.596	0.479	0.479
R^2	0.853	0.853	0.841	0.841	0.860	0.860
Industry-Year FE	Y	Y	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y	Y	Y

Notes: This table uses 1990-2007 NETS to estimate the difference-in-difference regressions of the form:

$$Y_{ist} = \alpha_i + \beta_t \text{DistToNode}_s + Z_{ct}\lambda + \delta_{jt} + \eta_{ft} + \varepsilon_{ist},$$

where the dependent variable is a measure of firm geographic span of control for firm i at location s in year t, and location is measured at the ZIP code level. α_i is firm fixed effect, DistToNode_s is the distance from location s to the nearest NSFNET node, Post_t is a dummy variable set to 1 for years since 1995, Z_{ct} is a vector of county-year characteristics, δ_{jt} is industry-year fixed effect, η_{ft} is state-year fixed effect, and ε_{ist} is the error term. Regressions are weighted by firms' employment share in each year. The dependent variable is the number of counties a firm has for column (1) and (2), the number of counties a multi-unit firm has for column (3) and (4), and a dummy variable set to 1 for multi-unit firms for column (5) and (6). Firm fixed effect, industry-year fixed effect and state-year fixed effects are included in all columns. Column (2), (4), and (6) control for additional county characteristics. Standard errors are clustered at the firm level.

D Estimation

Let a firm i be headquartered at location o and have a set of locations denoted by S. At each non-headquarter establishment s, the ratio of wage payment to local production workers to sales is a constant and equals to $(1-\alpha)(\sigma-1)/\sigma$. Then, the wage payment is

$$\begin{aligned} w_s L^i_{oS,s} &= (1-\alpha)\frac{\sigma-1}{\sigma}\text{sales}^i_{oS,s} \\ &= (1-\alpha)\frac{\sigma-1}{\sigma}\tilde{\Gamma}\left(\frac{\sigma-1}{\sigma}\right)^{\sigma-1}\left(\frac{z^i}{h(\varphi^i)^\alpha}\right)^{\sigma-1}\sum_k P^\sigma_k Y_k \Phi^{\frac{\sigma-1}{\theta}-1}_{oSk}\left[\frac{T_s}{\tau_{sk}}\left(\frac{1-\alpha}{w_s}\right)^{1-\alpha}\left(\frac{\alpha}{w_o d_{os}}\right)^\alpha\right]^\theta \\ &= (1-\alpha)\tilde{\Gamma}\left(\frac{\sigma-1}{\sigma}\right)^{\sigma}\left(\frac{z^i}{h(\varphi^i)^\alpha}\right)^{\sigma-1}\left[T_s\left(\frac{1-\alpha}{w_s}\right)^{1-\alpha}\left(\frac{\alpha}{w_o d_{os}}\right)^\alpha\right]^\theta\sum_k P^\sigma_k Y_k \Phi^{\frac{\sigma-1}{\theta}-1}_{oSk}\tau^{-\theta}_{sk} \end{aligned} \tag{.30}$$

Then, the employment at location s is

$$\begin{aligned} L^i_{oS,s} &= w_s^{-1}(1-\alpha)\tilde{\Gamma}\left(\frac{\sigma-1}{\sigma}\right)^{\sigma}\left(\frac{z^i}{h(\varphi^i)^\alpha}\right)^{\sigma-1}\left[T_s\left(\frac{1-\alpha}{w_s}\right)^{1-\alpha}\left(\frac{\alpha}{w_o d_{os}}\right)^\alpha\right]^\theta\sum_k P^\sigma_k Y_k \Phi^{\frac{\sigma-1}{\theta}-1}_{oSk}\tau^{-\theta}_{sk} \\ &= (1-\alpha)^{(1-\alpha)\theta+1}\alpha^{\alpha\theta}\tilde{\Gamma}\left(\frac{\sigma-1}{\sigma}\right)^{\sigma}\left(\frac{z^i}{h(\varphi^i)^\alpha}\right)^{\sigma-1}T^\theta_s w_s^{-\theta(1-\alpha)-1}(w_o d_{os})^{-\alpha\theta}\sum_k P^\sigma_k Y_k \Phi^{\frac{\sigma-1}{\theta}-1}_{oSk}\tau^{-\theta}_{sk} \end{aligned} \tag{.31}$$

Similarly, at each non-headquarter establishment s, the ratio of wage payment to management to sales is also a constant and equals to $\alpha(\sigma-1)/\sigma$. Then, the wage payment to the headquarter management workers is

$$\begin{aligned} w_o M^i_{oS,s} &= \alpha\frac{\sigma-1}{\sigma}\text{sales}^i_{oS,s} \\ &= \alpha\tilde{\Gamma}\left(\frac{\sigma-1}{\sigma}\right)^{\sigma}\left(\frac{z^i}{h(\varphi^i)^\alpha}\right)^{\sigma-1}\left[T_s\left(\frac{1-\alpha}{w_s}\right)^{1-\alpha}\left(\frac{\alpha}{w_o d_{os}}\right)^\alpha\right]^\theta\sum_k P^\sigma_k Y_k \Phi^{\frac{\sigma-1}{\theta}-1}_{oSk}\tau^{-\theta}_{sk} \end{aligned} \tag{.32}$$

The headquarter employment required for production at establishment s is

$$\begin{aligned} M^i_{oS,s} &= w_o^{-1}\alpha\tilde{\Gamma}\left(\frac{\sigma-1}{\sigma}\right)^{\sigma}\left(\frac{z^i}{h(\varphi^i)^\alpha}\right)^{\sigma-1}\left[T_s\left(\frac{1-\alpha}{w_s}\right)^{1-\alpha}\left(\frac{\alpha}{w_o d_{os}}\right)^\alpha\right]^\theta\sum_k P^\sigma_k Y_k \Phi^{\frac{\sigma-1}{\theta}-1}_{oSk}\tau^{-\theta}_{sk} \\ &= (1-\alpha)^{(1-\alpha)\theta}\alpha^{\alpha\theta+1}\tilde{\Gamma}\left(\frac{\sigma-1}{\sigma}\right)^{\sigma}\left(\frac{z^i}{h(\varphi^i)^\alpha}\right)^{\sigma-1}T^\theta_s w_s^{-\theta(1-\alpha)}w_o^{-\alpha\theta-1}d_{os}^{-\alpha\theta}\sum_k P^\sigma_k Y_k \Phi^{\frac{\sigma-1}{\theta}-1}_{oSk}\tau^{-\theta}_{sk} \end{aligned} \tag{.33}$$

Thus, total management employment at the headquarter is $M^i_{oS} = \sum_{s\in S} M^i_{oS,s}$ where $M^i_{oS,s}$ is defined above. Together with the local production workers, total employment at the headquarter is $L^i_{oS,HQ} = L^i_{oS,o} + \sum_{s\in S} M^i_{oS,s}$, where $L^i_{oS,o}$ and $M^i_{oS,s}$ are defined by Equation (.31) and (.33), respectively.

Therefore, the ratio of employment at a non-headquarter establishment to that at the headquarter is

$$
\begin{aligned}
\tilde{\zeta}_{oS,s} &= \frac{L^i_{oS,s}}{L^i_{oS,HQ}} \\
&= \frac{T_s^\theta w_s^{-\theta(1-\alpha)-1} d_{os}^{-\alpha\theta} \sum_k P_k^\sigma Y_k \Phi_{oSk}^{\frac{\sigma-1}{\theta}-1} \tau_{sk}^{-\theta}}{T_o^\theta w_o^{-\theta(1-\alpha)-1} \sum_k P_k^\sigma Y_k \Phi_{oSk}^{\frac{\sigma-1}{\theta}-1} \tau_{ok}^{-\theta} + \frac{\alpha}{1-\alpha} w_o^{-1} \sum_{s\in S} T_s^\theta w_s^{-\theta(1-\alpha)} d_{os}^{-\alpha\theta} \sum_k P_k^\sigma Y_k \Phi_{oSk}^{\frac{\sigma-1}{\theta}-1} \tau_{sk}^{-\theta}}
\end{aligned}
$$

Take logarithm of $\zeta_{oS,s}$, and we can get that

$$
\begin{aligned}
\log \tilde{\zeta}_{oS,s} = {} & \theta \log T_s - [\theta(1-\alpha)-1] \log w_s - \alpha\theta \log d_{os} + \log \left(\sum_k P_k^\sigma Y_k \Phi_{oSk}^{\frac{\sigma-1}{\theta}-1} \tau_{sk}^{-\theta} \right) \\
& - \theta \log T_o + [\theta(1-\alpha)+2] \log w_o - \log \left(\sum_k P_k^\sigma Y_k \Phi_{oSk}^{\frac{\sigma-1}{\theta}-1} \tau_{ok}^{-\theta} \right) \\
& - \log \frac{\alpha}{1-\alpha} - \log \left(\sum_{s\in S} T_s^\theta w_s^{-\theta(1-\alpha)} d_{os}^{-\alpha\theta} \sum_k P_k^\sigma Y_k \Phi_{oSk}^{\frac{\sigma-1}{\theta}-1} \tau_{sk}^{-\theta} \right)
\end{aligned}
$$

Finally, we can write the log employment at each non-headquarter establishment, scaled by headquarter employment, by

$$
\log \tilde{L}^i_{oS,s} \equiv L^i_{oS,s} - \log L^i_{oS,HQ} = -\alpha\theta \log d_{os} + \log \left(\sum_k P_k^\sigma Y_k \Phi_{oSk}^{\frac{\sigma-1}{\theta}-1} \tau_{sk}^{-\theta} \right) + \xi_s + \xi_{oS}, \quad (.34)
$$

where

$$
\begin{aligned}
\xi_s &= \theta \log T_s - [\theta(1-\alpha)-1] \log w_s && (.35) \\
\xi_{oS} &= -\theta \log T_o + [\theta(1-\alpha)+2] \log w_o - \log \left(\sum_k P_k^\sigma Y_k \Phi_{oSk}^{\frac{\sigma-1}{\theta}-1} \tau_{ok}^{-\theta} \right) \\
& \quad - \log \frac{\alpha}{1-\alpha} - \log \left(\sum_{s\in S} T_s^\theta w_s^{-\theta(1-\alpha)} d_{os}^{-\alpha\theta} \sum_k P_k^\sigma Y_k \Phi_{oSk}^{\frac{\sigma-1}{\theta}-1} \tau_{sk}^{-\theta} \right) && (.36)
\end{aligned}
$$

E Counterfactuals

E.1 Gains from Multi-Unit Production and Trade

Similar to the gains from ICT, gains from trade and multi-unit production are the proportional changes in the ideal price indexes, i.e. P_s, as we move from the counterfactual equilibrium with 1) multi-unit production but no trade (i.e. $\tau_{ss'} \to \infty$) and 2) trade but no multi-unit production (i.e. $f_{os}^X \to \infty$). Table 21 reports the results.

Column (1)–(2) report the gains from trade. With the baseline estimates, the gains from trade range from 3% decrease in the ideal price index in the Pacific division to the 14.7% in the New England division. Similar to the conventional view, the gains are proportional to the location's average trade cost to the other locations. Additionally, I compare the benchmark model with a model absent of multi-unit production. The benchmark model yields *smaller* gains from trade compared to a trade-only model, suggesting that trade and multi-unit production are substitutes.

Furthermore, the model without multi-unit production predicts different distributions of gains across locations. In the model without multi-unit production, the Mountain division would benefit most while the benchmark model predicts moderate gains from trade for this division. Even without trade, firms could have expanded to the Mountain division as its fixed cost of setting up establishments is relatively low.

Column (3)–(4) report the gains from multi-unit production. Through the lens of the benchmark model, the gains from multi-unit production are larger than those from trade, ranging from 20.1% reduction in the price index in the East North Central division to 35.5% in the Mountain division. Similarly, a model without trade would *overstate* the gains from multi-unit production, suggesting that multi-unit production is a substitute of trade. That said, a model without trade does not change the relative gains from multi-unit production across locations.

E.2 DID Estimates of the Internet Privatization: PE or GE Effects?

This appendix section shows that the difference-in-difference estimates of the Internet Privatization reflect partial equilibrium effects. Suppose the firm's geographic span of control is in the form of:

$$\text{FirmSpanControl}_{ist} = a_{ist} + b^{ICT}\gamma_{ist} + \boldsymbol{P}_t \boldsymbol{b}^{P,r} + \boldsymbol{X}_{ist}\boldsymbol{b}^X + u_{ist}, \tag{.37}$$

where I denote firm by i, firm's location by s, region where the prices are formed by r, and time by t. a_{ist} denotes firm productivity, γ_{ist} denotes within-firm communication cost,

$\boldsymbol{P}_t = \{P_{rt}\}$ denotes a vector of regional prices, $\boldsymbol{X}_{ist}$ denotes a vector of firm- and location-specific characteristics, and u_{ist} denotes a stochastic error term. As we do not directly observe from data the communication cost γ_{ist} and this cost is likely to be correlated with firm productivity, in the difference-in-difference analysis I use a firm's distance to the nearest Internet backbone nodes interacted with the time dummy of Internet privatization as a proxy for the communication cost:

$$\text{FirmSpanControl}_{ist} = a_{ist} + b^{ICT}\text{DistToNode}_s \times \text{Post}_t + \boldsymbol{P}_t\boldsymbol{b}^{P,r} + \boldsymbol{X}_{ist}\boldsymbol{b}^X + u_{ist}. \quad (.38)$$

The Internet privatization, however, may change the regional prices as well. Then, the coefficient from the reduced-form regression reflects not only the effect of communication cost b^{ICT}, but also regional prices $b^{P,r}, r = 1, ..., N$ through general equilibrium. Fortunately, my identification comes from variations at the location (i.e. ZIP code) that is finer than the one where prices are formed. Therefore, we can control for the regional general equilibrium effects by region fixed effects. In particular, I include state-year fixed effects δ_{rt} in my preferred specification:

$$\text{FirmSpanControl}_{ist} = a_{ist} + b^{ICT}\text{DistToNode}_s \times \text{Post}_t + \delta_{rt} + X_{ist}b^X + u_{ist}. \quad (.39)$$

Any general equilibrium effects through regional prices, including wages and ideal price indexes of manufacturing products, are not captured by the coefficient on the interaction term. We can thus interpret b^{ICT} as the *partial equilibrium* effect of the Internet privatization on the firm's geographic span of control.

Table 19: Industry Concentration

	Benchmark Model			Trade-Only Model		
	Top 1% (1)	Top 10% (2)	Top 20% (3)	Top 1% (4)	Top 10% (5)	Top 20% (6)
A. Industry Concentration Absent ICT						
National	0.62	0.93	0.96	0.48	0.85	0.90
New England	0.33	0.77	0.90	0.47	0.85	0.93
Middle Atlantic	0.40	0.81	0.92	0.47	0.85	0.93
East North Central	0.40	0.81	0.92	0.47	0.85	0.93
West North Central	0.34	0.77	0.90	0.47	0.85	0.93
South Atlantic	0.37	0.79	0.90	0.47	0.85	0.93
East South Central	0.33	0.76	0.89	0.47	0.85	0.93
West South Central	0.36	0.77	0.89	0.47	0.85	0.93
Mountain	0.31	0.72	0.86	0.47	0.85	0.93
Pacific	0.37	0.79	0.91	0.47	0.85	0.93
B. %Change In Industry Concentration with Universal ICT Accessibility						
National	0.04	0.01	0.01	0.04	0.01	0.01
New England	0.06	0.03	0.01	0.04	0.01	0.01
Middle Atlantic	0.02	0.02	0.01	0.04	0.01	0.01
East North Central	0.04	0.02	0.01	0.04	0.01	0.01
West North Central	0.04	0.03	0.01	0.05	0.01	0.01
South Atlantic	0.03	0.02	0.01	0.04	0.01	0.01
East South Central	0.00	0.02	0.01	0.04	0.01	0.01
West South Central	-0.01	0.02	0.01	0.04	0.01	0.01
Mountain	-0.01	0.02	0.01	0.04	0.01	0.01
Pacific	0.02	0.01	0.01	0.04	0.01	0.01

Table 20: General Equilibrium Effects of the Internet Privatization on Manufacturing Price Indexes

Census Division	%Change in Manufacturing Price
New England	-1.92
Middle Atlantic	-1.85
East North Central	-2.03
West North Central	-1.78
South Atlantic	-1.65
East South Central	-2.04
West South Central	-1.60
Mountain	-1.77
Pacific	-1.52

Table 21: Gains from Trade and Multi-Unit Production

	Gains from Trade		Gains from MU	
	Benchmark	Trade-Only	Benchmark	MU-Only
%Change in Ideal Price Index	(1)	(2)	(3)	(4)
New England	-14.7	-25.6	-28.0	-37.2
Middle Atlantic	-9.2	-11.7	-23.4	-25.6
East North Central	-6.4	-6.5	-20.1	-20.2
West North Central	-14.3	-25.9	-28.8	-38.4
South Atlantic	-7.5	-13.0	-27.1	-31.5
East South Central	-13.3	-27.3	-32.9	-43.7
West South Central	-8.2	-16.2	-31.3	-37.3
Mountain	-10.0	-27.6	-35.5	-48.1
Pacific	-3.0	-4.6	-23.4	-24.6