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**Strategic Technology Adoption and Entry Deterrence
in the U.S. Local Broadband Markets**

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Strategic Technology Adoption and Entry Deterrence in the U.S. Local Broadband Markets*

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Abstract

How does strategic investment affect entry of new technologies and market structure? This article investigates the role of competition in firms' technology adoption decisions in the U.S. wireline broadband industry. I present a model of strategic entry deterrence and study how internet service providers' interactions affect their technology deployment at local markets. The goal is to capture an important trade-off: cable firms adopt a new cable system to provide higher speeds, but the adoption has a preemptive effect on fiber firms' entry. I collect and combine unique firm-level data on broadband technology deployment and markets under entry threat for New York State. I provide evidence of strategic investment by cable incumbents to deter fiber entry. Counterfactual scenarios suggest that the industry has experienced 16% excessive investment in cable adoption and 12% underinvestment in fiber entry both of which are explained by these deterrence strategies. In addition, subsidies to cable incumbents in small markets reduce fiber entry rate by 50%. I also find that policies that promote statewide entry mitigate the effects from these deterrence strategies and increase fiber entry rate by 30%. These results have wide implications for technology diffusion, quality provision and optimal subsidy policy in markets with strategic technology adoption and entry threat.

Keywords: Broadband, Strategic Investment, Technology Adoption, Entry Threat, Deterrence

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1 Introduction

"...those paying for 25 megabit service will get 50 megabits, those paying for 50 megabits will get 105, and those paying for 105 will get a whopping 150 megabits...

(Comcast, Kansas City, August 2014).

"The company, which is one of the biggest cable operators in Kansas City, is rolling out "major enhancements" to its services in the area, dubbed TWC Maxx. One of the main features is faster Internet speeds for customers at no additional charge."

(Kansas Business Journal, Kansas City, January 2015).

"...speed increases on TWC residential Internet plans at no additional cost, with customers experiencing increases up to six times faster..."

(TWC, Charlotte, April 2015).

Firms often invest excessively if they anticipate that a potential competitor may enter the market. This can happen for two reasons: first, they may prepare for a post-entry market structure, and, second, they may actually aim to deter entry by locking their customers in to high-quality products and, thus, making demand unsustainable for new firms. In this paper, I examine strategic investment decisions in the broadband industry in the form of technology adoption.

There is anecdotal evidence about cable incumbents adjusting their behavior to potential fiber entry in the broadband industry. The above news articles refer to significant speed improvements by large broadband providers in markets where Google Fiber deploys or plans to deploy optical fiber. Cable incumbents invest significantly in their networks to be able to offer significantly higher speeds in markets under the threat of fiber entry.

In this article, I ask the following questions: Do cable incumbents strategically invest because of fiber entry threat? What is the effect of this behavior on market structure? Also, if firms could pre-commit to investment strategies, how would fiber entry, market structure and technology diffusion change?

It is crucial to know why internet service providers (henceforth ISPs) invest in new technologies. If strategic investment is present, then technology adoption decisions may have significant welfare implications for two main reasons: first, incumbents' do not adopt when their profit is max-

imized but when they anticipate deterring entry. This incentive is different than upgrading networks because of high demand for bandwidth or the need to prepare for post-entry competition. Second, technologies that may be able to provide higher-quality products currently or in the future are deterred from entry because of cable incumbents' strategic advantage. In this case, in the short run, consumers may face a set of higher-quality products, but in the long run, this excessive investment may result in less competition and lower market equilibrium quality.

On the other hand, if firms anticipate that they cannot deter entry, firms' investment strategies may actually benefit consumers since incumbents prepare for post-entry market structure and offer higher-quality products while new firms enter in a more competitive market. In other words, the threat of entry itself may lead to faster technology diffusion and higher equilibrium quality.

I deploy a model of strategic investment in which cable incumbents make technology adoption decisions, and fiber firms decide whether or not to enter in each market. Incumbents have a strategic advantage because of lower investment costs and because of their prior investment. I solve a sequential game of incomplete information in which fiber firms observe cable incumbent's adoption decision before they enter. I define deterrence as the effect of incumbents' technology adoption on entrants' profits. The sequential nature of the game and the information asymmetry allow to solve for a sequential equilibrium.

I compare firm strategies when cable firms commit to an investment rule and when they do not. To accomplish that, I break technology adoption decisions into two effects: the direct effect (when a cable incumbent adopts based on demand and market structure) and the indirect effect (when a cable incumbent's adoption decision affects fiber entry and, thus, the future fiber firms' profitability). The deterrence effect is isolated when cable incumbent's action deviates from the optimal strategy and thus, indirect effect is zero. In addition, if incumbents make investment decisions to deter entry, the indirect effect should lead to excessive investment in the industry. This method does not require solving for simultaneous game equilibria to remove deterrence and thus, issues like multiplicity of equilibria or uniqueness are avoided.

I construct and combine a comprehensive dataset consisting of firm-level data on broadband deployment for the state of New York. I focus on New York since it is one of the most successful cases of broadband provision in the U.S., and it has experienced significant fiber entry over the last decade. My data consists of two main parts. First, data about technology deployment for cable incumbents and entry decisions by fiber potential entrants at the most local level. Second,

data about which markets fiber firms consider as potential markets. I identify potential entrants using fiber firms' entry announcements, licence agreements with local authorities and prior network presence.

I use variation in investment rates by cable incumbents and threat of fiber entry across markets to identify strategic effects. I show evidence that, first, cable adoption reduces the likelihood of fiber entry and, second, cable adoption increases non-monotonically with market attractiveness for potential entrants. This non-monotonicity in cable adoption implies that incumbents take into account the indirect effect on potential entrants when they make their investment decisions.

Several industry and stylized facts motivate my model. First, there are distinctive broadband technologies and related firms offering high-speed internet service. Second, the industry is characterized by quality improvement that occurs through building and upgrading broadband networks. Each incumbent cable firm may adopt a new cable system in each market and supply a higher-quality good. This implies that cable firms have a strategic advantage since the cost of adoption is smaller as compared to a potential fiber firm. In that sense, cable firms are "leaders" in the industry and fiber firms the "followers". Third, there is fiber entry in the local markets that affects the market structure. This implies that market structure is endogenous and is determined by how firms compete across technologies and local markets. Finally, fiber firms observe cable incumbents' technology decision before they make their entry decision.

In the first counterfactual scenario, removing the deterrence effect shows that the industry has experienced 16% excessive investment in cable adoption and 12% underinvestment in fiber entry compared to the observed rates. In the second counterfactual, I show that subsidizing cable incumbents in small markets leads to a significant drop in fiber entry by 50% while subsidizing potential fiber entrants increases fiber entry and cable adoption remains almost constant. These counterfactuals also imply that entry will not be deterred when fiber entrants commit to an entry rule such as entry announcements irrespective of cable incumbents' decision. In addition, it implies that policy makers should take into account these strategies in their subsidy programs.

In the third counterfactual scenario, I find that a policy that promotes statewide fiber entry decrease cable adoption rate by 22% and increase fiber entry rate by 30%. These results imply that lowering the local entry barriers may be a more efficient way to mitigate the entry deterrence effects.

This paper is related to and contributes to several streams of literature. First, it is linked to

the strategic investment literature. Although there is significant theoretical literature that examines this issue, there is only limited empirical work—partly because of the difficulty of distinguishing between competitive and deterrence effects. Second, this work is part of a small but growing literature on broadband and telecommunications focusing on entry patterns and strategic interaction of firms. To the best of my knowledge, this is the first paper to provide evidence of strategic investment in the broadband industry. In particular, this paper aims to identify whether firms choose to strategically upgrade their network to deter entry from fiber firms and, subsequently, the effect on market structure.

Third, this paper is related to the literature that examines technology diffusion. Although, there is significant work that measures the competitive effects of technology adoption, there is only limited work that quantifies the role of entry threat on technology diffusion. In addition, this is the first paper that considers the spatial nature of technology diffusion as a product of firms' strategic interactions and only one of the few that considers deterrence strategies in this process. Furthermore, this paper contributes to the literature that examines why new technologies may not enter some markets for reasons related to deterrence.

Finally, this paper aims to provide a general framework for how firms react to entry threat and how this affects their strategic behavior. There is a significant literature on limit pricing in the airline industry but only a limited body of work that provides evidence of firms' investment behavior before potential entrants become actual entrants. Investment in broadband networks creates a credible mechanism for post-entry competition that potential entrants will take into account in their entry decision.

Firms' investment strategies in broadband are crucial from a policy perspective. First, In addition, the discussion about investment in broadband networks is related to large-scale policy goals in the U.S. and elsewhere since high-speed internet is considered a vital factor for innovation and growth in the economy. Policy makers have repeatedly made suggestions for how the U.S. could become a leading power in broadband¹. The National Broadband Map² depicts some of these goals but leaves open the question of how firms' strategic interactions relate to issues such as last-mile broadband infrastructure and lower prices for better quality for consumers.

¹"All Americans should have affordable access to robust and reliable broadband products and services. Regulatory policies must promote technological neutrality, competition, investment, and innovation to ensure that broadband service providers have sufficient incentive to develop and offer such products and services." FCC Strategic Goals, 2009-2014.

²FCC, 2010.

Second, consumers have high switching costs and usually only a few provider choices. This necessitates the analysis of the industry at the most local level, where ISPs have market power (with the broader definition of the term) once they gain network access to a household. Since consumers cannot easily switch, firms may significantly reduce consumer welfare at the household level.

The paper proceeds as follows. Section 2 provides a description of the broadband technologies and the industry background. Section 3 describes how the paper is related to the prior literature. In Section 4, I describe the data and its variation that I use to identify deterrence and Section 5 provides some relative market and definition discussion. In section 6, I present some reduced-form evidence that implies strategic interactions of firms in the broadband industry. Section 7 presents the structural model, and Section 8 discusses the identification method. In Section 9, I discuss the estimation method and results. In Section 10, I discuss how the model fits the data. In section 11, I provide counterfactual scenarios. Section 12 provides a general discussion about the paper, its findings, limitations and future steps.

2 Industry Background

Broadband internet connection, the successor of narrowband technology (or dial-up), allows for higher-speed data transmission³ and an "always-on" feature. The broadband industry constitutes an extremely dynamic economic environment. In 2000, 4.4% of U.S. households had a broadband connection; by 2010, that number had jumped to 68% and by 2013, 72%⁴. Between December 2002 and December 2012, total (business and residential) fixed connections grew from 19 million to 93 million—at a compound annual growth rate of 17% per year⁵. Figure 1 shows that since 2008, the increase in broadband deployment has come mostly from the expansion of cable broadband, while the share of DSL broadband has declined. In addition, this figure shows that although optical fiber is the technology that offers the highest speeds, it has diffused only slowly.

Currently, there are three main wireline broadband technologies⁶: DSL, cable modem and optical fiber. Digital Subscriber Line (DSL), the technology deployed by telephone companies, trans-

³In most OECD countries, the threshold on defining an internet connection as a broadband connection is 256kbps. The FCC uses 200kbps as that threshold.

⁴"Four years of Broadband Growth Report", Office of Science and The National Economic Council.

⁵FCC yearly reports 2000-2012.

⁶Other broadband technologies are wireless are mobile and satellite broadband. In this paper, I do not examine these technologies.

mits data over the existing copper telephone lines. There are two variations: symmetric DSL and asymmetric DSL. The main difference between symmetric and asymmetric DSL is that the latter allows for more bandwidth for receiving and less for transmitting data, more for downloading than for uploading—and it is the prevalent form of DSL in the industry.

Figure 1: Broadband subscribership evolution in the U.S. (Source: FCC data).

Cable ISPs deploy broadband through their conventional cable TV network but with some technical modifications⁷. After 1996, cable ISPs started upgrading their network to handle higher data transmission—this became feasible with the *Data Over Cable Service Interface Specification (DOCSIS)* modem system. The DOCSIS modem system was released in 1997, the DOCSIS 2.0 upgrade in 2001 and DOCSIS 3.0 in 2006. A disadvantage of DOCSIS is that there is shared bandwidth for end users which may reduce the internet speeds. In addition, speed improvements are possible with the adoption of a new cable system. In 2016, DOCSIS 3.0 is the most widely deployed system in cable broadband. In addition, the transition to DOCSIS 3.0 is the most important improvement to cable broadband speeds.

Optical fiber technology usually offers the highest broadband speeds to its end users through fiber-to-the-home (FTTH). Through this technology, electronic signals are converted to light and

⁷For the description of the technical modifications of both DSL and cable networks see Spulber and Yoo (2009).

then transmitted through the optical fiber. Although cable and DSL firms may use optical fiber in their network, only fiber firms use fiber to the end user. This implies that FTTH is user-specific and there is no shared bandwidth.

With regard to speed, cable technology is able to offer higher broadband speeds compared to DSL because of the more available bandwidth, but service depends on the usage by other customers since the bandwidth is fixed and shared. On the other hand, through a DSL connection, the end-user has access to greater speed reliability since that is user-specific, but the bandwidth is usually less, and thus, the (download/upload) speeds are significantly lower. Optical fiber technology provides the highest speeds with high reliability.

Table 1 illustrates the difference of broadband mean speeds offered by ISPs in New York State. Optical fiber provides the highest speeds in the industry while there is a significant improvement of broadband speeds when cable firms switch from DOCSIS 2.0 to DOCSIS 3.0.

	<i>Mean Speed</i>
Cable DOCSIS 3.0 (mps)	260.88
Cable DOCSIS 2.0 (mps)	17.35
DSL (mps)	7.78
Optical Fiber (mps)	404.53

Table 1: Speed comparison across broadband technologies (*Source:* Broadband Map).

About the cost of deployment, for cable incumbents, the cost of network upgrades is relatively low as the large sunk investments already occurred during the cable TV network expansion⁸. DSL firms provide broadband connection through their conventional telephone lines networks, although some adjustment investment needs to be made. This involves mainly installing the necessary equipment to separate voice from internet data. For asymmetric DSL, this requires the household to be less than three miles from the local central office and its installed device⁹. The cost of optical fiber deployment depends on whether the ISP uses existing utility poles or new cables, aerial or buried installations and may vary significantly from region to region¹⁰.

⁸FCC estimated that the cost of upgrading network from DOCSIS 2.0 to DOCSIS 3.0 and providing speeds up to 50Mbps is approximately \$165 per house. See Broadband Assessment Model, FCC, 2010.

⁹This device is called a digital subscriber line access multiplexer (DSLAM).

¹⁰For instance, Google's total capital expenditures for deploying fiber in Kansas City for 149,000 households was approximately \$84 million. That is \$563 per household (source: Costquest, Bernstein analysis).

Regarding market structure, 17 ISPs account for 93% of the total US broadband market subscribers. The largest cable broadband providers have a 58% share of the overall market, with about 13 million more subscribers than the largest telephone companies¹¹.

In New York state, the major cable incumbents are Time Warner Cable which offers service across the state. Each household can usually access only one cable provider (if any) and/or a DSL provider. After 2010, there was a considerable switch to the new cable system and fiber entry. The major DSL and optical fiber firm is Verizon.

To sum up, DSL ISPs were the first to provide broadband service. After 1996, cable ISPs entered the market, and since then have competed with DSL ISPs while switching from system to system through network upgrades. In the mid-2000s and afterwards, fiber ISPs started deploying optical fiber, which may provide the highest speeds in the industry. However, cable ISPs can upgrade their modem system at considerably lower cost compared to a fiber ISP that deploys optical fiber.

3 Related Literature

This paper builds on four streams of the literature: studies that use entry models to deduce firms' incentives, the literature that examines strategic investment, the technology adoption and diffusion literature, and the broadband and telecommunications industry studies.

3.1 Literature on Strategic Investment, Technology Adoption and Entry

There is a large theoretical literature on strategic investment (Spence (1977), Salop (1979), Lieberman (1987)) and technology adoption (Tirole and Fudenberg (1985)) but only limited empirical literature—partly because of the difficulty of identifying strategic incentives. Hall (1990) and Ghemawat (1990) examine capacity expansion in the titanium dioxide industry and find evidence of preemptive strategy by Du Pont.

¹¹Cable companies offered service to approximately 47.86 million subscribers. The largest cable providers (in terms of total subscribers) were: Comcast (19.986 million), Time Warner (11.599 million), Charter (4.138 million), Cablevision (3.087 million), Suddenlink (1.017 million), Mediacom (949,000), Cable ONE (464,292), other major cable companies (6.664 million). Telephone companies offered service to approximately 34.87 million subscribers. The top DSL providers were AT&T (16.453 million), Verizon (8.939 million), CenturyLink (5.909 million), Frontier (1.781 million), Windstream (1.194 million), Fairpoint (332,620), Cincinnati Bell (261,700). Source: Leichman Research Group report 2013.

Schmidt-Dengler (2006) considers the timing of technology adoption for U.S. hospitals. Schmidt-Dengler separates the business stealing and the preemption motives using firms' strategies. I use a similar approach for identifying deterrence in which the firm cannot affect entrant's future profitability by removing the indirect effect of technology adoption. The difference with this paper is that I incorporate entry threat on incumbent's technology adoption decision as well as fiber firms' entry decisions.

This paper also contributes to the literature that studies technology diffusion and market structure. Technology diffusion is the process that the adoption spreads across markets. Gruber and Verboven (2001) and Parker and Roller (1997) focus on the diffusion of mobile telecommunications and find that market concentration is negative correlated with adoption of mobile phones. Seamans (2012) studies upgrades in the cable TV industry in relation to municipal entry threat. Instead, I study technology adoption in broadband as it relates to fiber entry and study the effects of entry deterrence on market structure and the diffusion of a new technology.

Goettler and Gordon (2011) examine the effect of competition on innovation and find a positive relationship. The difference with their paper is that I consider also the role of entry threat. Igami (2015) examines creative destruction in the hard disk drive industry. The difference with Igami's paper is that I consider the spatial dimension of technology diffusion while incumbents actually deter the entry of new technologies and have a strategic advantage over potential entrants.

Ellison and Ellison (2011) introduce an approach for identifying strategic investment using a cross-section of markets. The framework is the pharmaceutical industry, and they find that firms strategically invest in middle-sized markets prior to patent expiration. Ellison and Ellison (2011) find a nonmonotonic relation between investment and market size in the case of strategic investment. Dafny (2005) uses Ellison and Ellison (2011) arguments to examine hospital markets and finds that volume growth for procedures is larger in intermediate markets, implying an entry deterrence motive by the incumbents in these markets. In this paper, I use their arguments for detection of incumbent cable firms' behavior in a subset of potential markets. The difference with these papers is that I quantify the deterrence effect and show how it affect technology diffusion.

There is an extensive literature applying entry models. Bresnahan and Reiss (1991, 1994) examine isolated local markets and show that even with a small amount of data, we can deduce how market observable characteristics affect entry and market structure. Berry (1994) investigates entry in the airline industry assuming firm heterogeneity. These papers show that the game has a

unique equilibrium in the number of players, and, in addition, they assume that entry is independent across markets. I contribute to this literature by examining the role of strategic investment on entry deterrence. In addition, I contribute to the limited literature of sequential entry games with incomplete information.

Goolsbee and Syverson (2008) and Sweeting et al. (2016) investigate incumbents' incentives in the airline industry and their strategic decision to cut fares in markets where Southwest may potentially enter. I use arguments similar to theirs by deducing incumbents' investment decisions in markets where a fiber firm is a potential entrant. The difference with their papers is that I focus on strategic investment in the broadband industry. In addition, I use a new potential entry definition based on entry announcements, network presence or city level agreements. In addition, cable incumbents' investment is a credible mechanism because of its irreversibility.

By deploying a model of price and capacity competition, Snider (2009) investigates the predatory policies of American Airlines to deter entry. Chicu (2012) investigates the strategic capacity choice of firms in the cement industry. The difference with Chicu's paper is that I investigate strategic investment as an entry deterring mechanism and also consider discrete choices for the firms. In addition, I identify deterrence by examining the deviation in firm's equilibrium strategy when the deterrence effect is removed. This approach does not require solving for simultaneous game equilibria and thus, issues about equilibrium multiplicity and uniqueness are avoided.

3.2 Literature on Broadband and Telecommunications

This paper contributes to the small but increasing literature on broadband competition. To the best of my knowledge, the paper is the first that considers both technology adoption decisions and strategic investment in this industry.

Connolly and Prieger (2013) provide a descriptive investigation of the US broadband industry from June 2005 to 2008. Xiao and Orazem (2011) use data on the number of broadband providers in each zip code from 1999 to 2003. They apply a variant of Bresnahan and Reiss's (1991, 1994) static model and find that when the number of existing firms is between one and three, the fourth entrant has a small effect on competitive conduct. Using the same dataset for the years 2009-2004, Xiao and Orazem (2009) examine the strategies of potential entrants in a market and the threat of entrants from neighboring markets. The difference between these papers and mine is that I

investigate technology adoption and deterrence while using firm-level data. In addition, I consider the interrelation of strategic investment and entry rather than strategic entry.

Nevo et al. (2013) use high-frequency data to estimate the demand for residential broadband. They examine the effect of a three-part tariff as a solution to network congestion. Instead, I consider an entry model and providers' strategic interactions at the local market level. In addition, I focus on the investment decision of ISPs.

Fan and Xiao (2013) use a dynamic entry model for the deregulated telephone industry and examine the effect of subsidies in the US local telephone markets. Fan and Xiao estimate their model building on Pakes et al. (2007). My paper differs from these two studies in that, first, I investigate the broadband industry; second, I examine cable firms' technology adoption decisions; and, finally, I consider how cable firms strategically make these decisions to deter entry.

Greenstein and McDevitt (2011) construct a price index for the broadband industry for the period 2004-2009. They find a modest price decline of broadband services. More specifically, they find the decline in quality-adjusted prices to be between around 3% and 10% in the period examined.

Distaso et al. (2006) examine the intra-platform and inter-platform competition in broadband services across EU countries and find that inter-platform competition promotes adoption, while competition in DSL services does not seem to play a crucial role. In their paper, the competing platforms are DSL and cable services.

Denni and Gruber (2005) also investigate the role of intra-platform and inter-platform competition in broadband adoption and find that intra-platform competition has a positive impact only in the short run (or in the early stage of broadband deployment), while inter-platform competition drives the diffusion in the long run. My paper, instead, follows a micro-level (e.g., firm-level actions and local markets) approach to investigate the incentives of firms in the industry, using an investment and entry model.

4 Data

The dataset for the state of New York is compiled from three different sources: 1) ISP-level data for the New York State; 2) ISP-level data about fiber firms' potential markets; and 3) U.S. Census

market-level data on demographics¹².

4.1 ISP-level data

The first dataset is the U.S. National Broadband Map (henceforth NBM), which is compiled by the FCC¹³, NTIA¹⁴ and New York State. This dataset is the largest data collection project about the U.S. broadband industry.

The dataset contains the majority of the total providers in the state. This dataset provides ISP-level data on broadband provision at the block level, their broadband technology deployment, product characteristics (i.e., download and upload speed) and ISP's identity for the period 2011-2013. The time interval is six months. Table 2 provides some summary statistics¹⁵. The table implies that markets are oligopolistic and have on average a cable incumbent and a DSL firm.

	Mean	SD	Median	Max
Cable adoption	0.04	0.20	0	1
Fiber entry	0.08	0.28	0	2
DSL ISPs	1.55	0.51	2	3
DOCSIS 2.0 ISPs	0.04	0.2	0	2
DOCSIS 3.0 ISPs	1.1	0.37	1	2
Fiber ISPs	0.98	0.84	1	6

Table 2: Summary Statistics. Obs. is market/t.

The initial dataset is at the block level. I aggregate the data at the census block group level by using the maximum speed that each provider offers in a block group. In addition, I assume that if an ISP offers a particular technology in a block, it may offer it in the block group as well. The reason for this aggregation is twofold: first, tractability (since the initial data contain more than 6 million observations), and second, the ability to match information with demographics¹⁶ at the census block group level.

A census block group is a group of census blocks with a population of 600 to 3,000 people. It is the smallest geographical unit for which US census provides demographic information. A census

¹²Further details and explanation about the data are provided in the appendix.

¹³Federal Communications Commission

¹⁴National Telecommunications and Information Administration

¹⁵I provide exact definitions in the next section.

¹⁶U.S. Census publishes demographics from the census block group level and above.

tract is a higher geographical level comprising multiple block groups. For a city, a block is usually bounded by streets, whereas for smaller cities or rural areas, there are many other factors (highways, rivers, mountains, etc.). These geographical units do not overlap. There are approximately 15,400 block groups in the state of New York and approximately 211,000 in the U.S.

In Figures 2-4, I provide geographical information about the transition to the cable modem system and optical fiber ISPs at the census tract level¹⁷. The goal is twofold: first, to illustrate the limited consumer options and, second, the transition of technologies. I use the maximum number of ISPs of a local market at each census tract¹⁸.

Figure 2 displays the areas that have DOCSIS 2.0. There is a clear reduction in areas where cable providers offer the old system. In Figure 3, I illustrate the areas that cable incumbents offered DOCSIS 3.0. Figure 4 indicates significant fiber entry in area in central NY State and in urban areas. In addition, it is clear that consumer had only a few options for high-speed internet from optical fiber¹⁹. Table 3 shows the technology evolution across markets for Time Warner (which is the largest cable incumbent):

	Jun, 2011	Jun, 2012	Jun, 2013
TWC 2.0 markets	2,678	1,610	313
TWC 3.0 markets	6,647	7,757	9,202
Markets with fiber	2,523	2,976	3,295

Table 3: Cable DOCSIS and Optical Fiber evolution. Obs. is market/t.

Although the dataset is comprehensive and provides information about the coverage at the most local level, it does have some limitations. First, there is no information about the number of subscribers, prices or contract promotions. Second, the data are compiled based on ISPs' responses to a survey. We may anticipate that firms have an incentive to overreport their coverage. Although this is self-reporting probably affects more the speed reported and less the technology deployed since technology deployed is easier to detect. Finally, a large number of local markets have already switched to the new cable system.

¹⁷At this level for visual reasons.

¹⁸In other words, instead of summing the total ISPs in a census tract, I use what is the largest number of ISPs in a block group that a consumer can find in a block group.

¹⁹New York City is an exception.

Regions with a cable provider offering DOCSIS in 2011.

Regions with a cable provider offering DOCSIS in 2011.

Figure 2: Cable DOCSIS 2.0 evolution in NYS.

Regions with a cable provider offering DOCSIS in 2011.

Regions with a cable provider offering DOCSIS in 2013.

Figure 3: Cable DOCSIS 3.0 adoption evolution in NYS.

Regions with a fiber provider in 2011.

Regions with a fiber provider in 2013.

Figure 4: Fiber deployment evolution in NYS.

4.2 Data on fiber firms' potential markets

I compile a dataset on which markets fiber providers consider a potential market. This includes ISP agreements with local authorities about covering an area, as well as internet archives on prior announcements of which area or cities they will cover or where these firms previously owned dark fiber (dormant) networks.

This dataset is compiled at the city level. I assume that if a provider makes an announcement or has a license about potentially offering service in a city, then all census block groups are considered potential markets. Almost 70% of the total local markets in the state have at least one potential fiber entrant²⁰.

An advantage of these data is that they a spatial variation of which markets are under threat of fiber entry. The disadvantage is that I do not observe time variation in the set of potential markets for each fiber firm. I provide additional information on this data and its construction in the Appendix, Section A.1.

4.3 Demographics data

Finally, I use demographics information from the US Census for the local markets. More specifically, I obtain population and aggregate household income. In the estimation, I use population density as population divided by the area of a local market.

5 Relative Market Discussion and Definitions

I now define the broadband market in the product and geographical space. The definition of a market needs to satisfy two conditions: first, consumers have the same choice set, and second, ISPs face the same set of competitors. Ideally, this would imply that each household is a different market. To make the analysis tractable, I will need to make some simplifying assumptions.

First, the product space encompasses wireline or fixed broadband service provided by DSL, cable or fiber ISPs²¹. There are other wireline broadband technologies available (e.g. copper wire)

²⁰This is usually just one potential entrant per market and at some rare cases two.

²¹I do not include wireless, mobile or satellite service in the product space. The share of satellite service is around 3% of the total market) while mobile broadband for household use is even lower. In addition, the average speeds of these technologies are currently

but have only a small share of total connections. In addition, about the DSL technology, I focus on asymmetric DSL (or ADSL) and not symmetric (SDSL) mainly for two reasons: first, because it is the dominant DSL version in the industry and second, most DSL providers offer both while it is not common SDSL to be offered while ADSL not²².

Second, with regard to the geographical space, I examine ISPs' decisions using a census block group²³ as a local market. This implies the assumption that consumers of the same census block group will have the same choice set. In addition, I assume that if a provider offers service in a block, then it may offer service in the entire block group²⁴.

Within this framework, I refer to technology adoption when a cable ISP currently offering DOCSIS or DOCSIS 2.0 switches to DOCSIS 3.0 at a local market. This switch is a credible commitment for cable firms since it gives them the ability to offer a much higher-quality product than previously (as analysed above), and it cannot be reversed.

A potential entrant is a fiber ISP. In this paper, fiber entry is defined as a fiber ISP offering broadband service in a local market where had not done so before. Also, I abstract from cable entry in new markets since it was not a common business strategy during the period examined. A potential fiber entrant is a firm that could enter a potential market (as defined above) but it does not enter.

6 Evidence of strategic deterrence on cable adoption

This section provides evidence of strategic investment by cable incumbents. To identify strategic effects, I focus on markets under threat of entry and in which Time Warner is the major incumbent. I present two sets of reduced-form evidence of strategic deterrence in the local broadband markets.

The first set of evidence shows that cable adoption by the cable incumbent can actually deter fiber entry. If cable adoption makes fiber entry less likely, then this implies that it may create an incentive for cable firms to adopt faster to keep the market less competitive.

The second set of evidence shows that cable adoption varies non-monotonically in the likeli-

much lower than that of wireline broadband.

²²That means that when I refer to DSL, I refer to ADSL.

²³Census block group is a geographically lower level compared to county, as defined by the U.S. Census.

²⁴Note that the broader geographical definition of a market we use, the more information about investment decisions we lose since there is a significant variation at the most local level. This implies that ISPs compete locally for new customers.

hood of fiber entry in markets that are under threat of entry. This follows Ellison and Ellison's (2011) argument about identifying the incumbent's strategy in the case of deterrence motives and in which entry likelihood varies with market attractiveness for the potential entrants.

In this framework, cable firms adopt faster in markets with an intermediate threat of entry because they may actually be able to deter entry. On the contrary, in small markets, demand would determine whether to adopt since the market is small enough, while in high-demand markets fiber entry may occur irrespective of cable adoption. If deterrence motives were absent, we would expect the cable adoption probability to be higher the more attractive the market is for potential fiber entrants.

6.1 Determinants of Fiber entry

This section examines the competitive effects of cable adoption on fiber entry to determine whether cable adoption has a preemptive effect on fiber entry. I focus on markets in which Time Warner is the major incumbent and there is at least one potential entrant. The total number of these markets is 6,660. I use the following logit specification:

$$y_{i,m,t}^f = \alpha X_{m,t} + \beta Z_{m,t} + \alpha_t + \alpha_{i, \text{county}} + \gamma_1 I\{TW \text{ 3.0 adoption}\}_{m,t} + \epsilon_{i,m,t}^f \quad (1)$$

where $y_{i,m,t}^f$ is the entry dummy for a fiber firm i in local market m ; $X_{m,t}$ is a matrix of market characteristics (population density and aggregate household income); $Z_{m,t}$ are market structure characteristics (number of DSL firms, fiber firms); and α_t corresponds to period t effects, $\alpha_{i, \text{county}}$, and corresponds to firm-county fixed effects, respectively. I include county-firm fixed effects to allow for differences in ISPs' deployment for different areas. I is the indicator function; *Time Warner 3.0 adoption* indicates whether Time Warner has adopted in market m ²⁵, and $\epsilon_{i,m,t}^f$ is a logit error.

The results are shown in Table 4. I report marginal effects. The results indicate that fiber firms prefer to enter in more densely population markets. This market characteristic matters for all

²⁵In the appendix, I allow entry in neighboring markets and thus for different choice sets (10km and 20km radii or the whole state) for fiber firms' entry.

specifications ²⁶ and ranges from 0.004% to 0.007%. In addition, the number of existing DSL and fiber ISPs, which can be perceived as a demand characteristic, is positive in all specifications.

Importantly, cable adoption has a negative effect on fiber entry. When time fixed effects are included, Time Warner adopting leads to a reduction of the likelihood of fiber entry by -2.8% while including firm/county reduces this likelihood to -2.1%. The mean likelihood of fiber entry is 9%.

P(Fiber entry_{jmt})	(1) Marginal Effect	(2) Marginal Effect	(3) Marginal Effect
Log(Pop density _{mt})	0.007*** (0.00)	0.005*** (0.00)	0.004*** (0.00)
Log(Agg hh inc) _{mt}	-0.003** (0.00)	-0.002*** (0.00)	-0.002* (0.00)
DSL firms _{mt}	0.050** (0.00)	0.041*** (0.00)	0.004 (0.00)
Fiber firms _{mt}	0.029*** (0.00)	0.023*** (0.00)	0.040*** (0.00)
Time Warner 3.0 _{mt}	-0.023 (0.01)	-0.028* (0.014)	-0.021* (0.01)
Time FE		Yes	Yes
Firm/County FE			Yes
Number of obs.	38,536	38,536	26,346
R-squared	0.198	0.365	0.451

* p < 0.05, ** p < 0.01, *** p < 0.001

Table 4: Determinants of fiber entry. Markets that are under threat of fiber entry and in which Time Warner is the major cable incumbent. Marginal effects from the logit specification are reported.

In Appendix, Section A.2, I use an alternative potential entry definition that does not change the negative effect but, rather, its magnitude. In particular, I consider fiber entry only in neighboring markets where firms already offer service. The effect of Time Warner adoption is again negative in all specifications.

6.2 Cable adoption and potential entry

In the second empirical specification, I examine how potential fiber entry likelihood affects the cable incumbent's adoption decision. The goal is to examine the cable incumbent's adoption strategy in markets in which cable firms face entry threat and have not adopted yet. Following

²⁶The variable population density is defined as 000s people per km².

Ellison and Ellison (2011), I show evidence that in markets with moderate attractiveness (as defined by predicted fiber entry), the cable incumbent is more likely to adopt. If there were no deterrence motives, we should expect cable adoption likelihood to be a positive function of fiber entry in markets under entry threat.

I estimate two specifications to capture the relationship of predicted cable adoption and entry threat. I show the results and marginal effects in Table 5. In the first specification, I focus on the markets in which Time Warner has not adopted yet (with or without fiber entry threat). I use the dummy $y_{i,m,t}^c$ that takes the value 1 when a cable firm decides to adopt and estimate a logit model using variation in which markets are under fiber entry threat. Equation (2) summarizes the logit specification:

$$y_{i,m,t}^c = \alpha X_{m,t} + \beta Z_{m,t} + \alpha_t + EntryThreat_m + \epsilon_{i,m,t}^c \quad (2)$$

where i is a cable firm; m is market and t is the time period; $X_{m,t}$ is a matrix of market characteristics (population and aggregate income) at time t , $Z_{m,t}$ are market structure variables (number of cable, DSL or fiber firms); and α_t corresponds to period t fixed effects. The variable $EntryThreat$ is a dummy indicating whether the market m is under the threat of fiber entry from a potential fiber entrant. Column (1) of Table 5 shows the results of equation (2). I find that the cable incumbent is 36% more likely to adopt in markets under the threat of fiber entry.

In the next specification, I use two stages to examine cable incumbent's investment strategy in markets under entry threat. In the first stage, I run a logit specification on exogenous market characteristics to predict fiber entry. The goal is to predict fiber entry in markets in which Time Warner is the dominant cable incumbent. From this stage, I receive the predicted fiber entry likelihood $Pr(\widehat{Entry})_{mt}$. I present the results of first stage in Appendix, Section A.3.

In the second stage, I use $Pr(\widehat{Entry})_{mt}$ as an explanatory variable in cable incumbent's adoption decision.

$$y_{i,m,t}^c = \alpha X_{m,t} + \beta Z_{m,t} + \alpha_t + Pr(\widehat{Entry})_{mt} + (Pr(\widehat{Entry})_{mt})^2 + \epsilon_{i,m,t}^c \quad (3)$$

Column (2) of Table 4 presents the results, which indicate a quadratic relationship between the likelihood of cable adoption and fiber entry, which is statistically significant.

P(Cable adopts_{jmt})	(1) Marginal Effect	(2) Marginal Effect
Log(Pop density _{mt})	0.079*** (0.01)	0.136*** (0.01)
Log(agg hh inc) _{mt}	0.132*** (0.02)	0.101** (0.03)
DSL firms _{mt}	0.002 (0.02)	-0.060* (0.03)
Fiber firms _{mt}	0.081*** (0.02)	0.244*** (0.05)
Entry Threat _m	0.360*** (0.04)	
$Pr(\widehat{Entry})_{mt}$		0.604** (0.23)
$Pr(\widehat{Entry})_{mt}^2$		-0.064** 0.02
Number of obs.	5,629	1,986
R-squared	0.502	0.5154

[^]p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Table 5: Cable adoption, entry threat and predicted fiber entry. Column (1) includes the set of markets in which Time Warner is the major cable incumbent. Column (2) includes markets under entry threat and in which Time Warner is the major cable incumbent. Time fixed effects are included. Standard errors are clustered at the Census tract level.

If cable firms do not strategically invest, we should observe a linear relationship since higher-demand market are more profitable to adopt. Instead, Table 5, Column (2) indicates that cable firms take into account potential fiber entry when they make their decisions and this decision is a concave function. Note that this is not just a competitive effect or preparation for a post-entry market structure since in that case, we should just observe a positive linear relationship.

7 A model of strategic technology adoption

In the model, there are two types of firms that make decisions: incumbent cable firms that make investment decisions and potential fiber entrants that decide whether or not to enter the local market. Incumbents' investment takes the form of technology adoption at the local-market level, and it is irreversible²⁷. I assume that these incumbents are long-lived, in the sense that they serve

²⁷Note that this makes the post-entry payoffs a credible commitment for the incumbent.

the market forever²⁸.

For potential entrants, the form of entry is building a fiber network and, thus, offering broadband service. Once a potential entrant builds its network, it becomes an entrant and stays in the market forever. A fiber firm can enter only a set of potential markets, which I assume is exogenous and constant over time.

I also assume that each firm may use one distinctive technology (cable or fiber) at most. Furthermore, about the order of moves, I assume that the game is sequential and the order is exogenous. Cable incumbent moves first, and the potential fiber entrants second²⁹. In addition, I assume that firms provide a homogeneous good.

Time is discrete, indexed by t and with finite horizon $t=2$. Let d_{jmt}^c be a dummy variable that takes the value 1 when a cable firm adopts and, thus, represents the technology adoption decision by the incumbent cable firm j in market m at time period t . This variable involves investment and a switch to the new cable system at the local market. Respectively, d_{jmt}^f is the dummy variable that indicates entry of a fiber firm in a local market m at time period t . Cable incumbents' and fiber entrants' profits are parameterized as functions of demand and the number of competitors in the market at time t according to:

$$\Pi_{jmt}^c = \theta_{jcD}D_{mt} + \theta_{jcDSL}n_{mDSLt} + \theta_{cF}n_{mft} - CI\{j = 1\} + \epsilon_{jmt}^c \quad (4)$$

$$\Pi_{1mt}^f = \theta_{fD}D_{mt} + \theta_{fDSL}n_{mDSLt} + \theta_{fC}n_{m3.0t} + \theta_{fF}n_{mft} - EC + \epsilon_{1mt}^f \quad (5)$$

where i is firm; j is choice; d is the firm choice, D_{mt} is the market size; n_{mDSLt} , $n_{m3.0}$ and n_{mft} are the number of DSL, DOCSIS 3.0 and fiber firms in market m , respectively. In addition, incumbent cable firms pay sunk adoption cost C if they choose to adopt the new cable system. Fiber firms pay an entry cost of EC if they decide to enter.

Assumption 1 $D_{mt} = D(\text{popdensity, aggregate household income})_{mt}$

Assumption 1 states that market size is determined by a function of local market exogenous

²⁸Note that incumbents may make technology adoption decisions for two reasons. They may want to respond to an increasing demand and offer a product of higher quality or make demand unsustainable for an entrant. Thus, this adoption decision may also have an preemptive effect on potential entrants.

²⁹This assumption is driven by the industry background.

characteristics. I assume that function D is linear³⁰.

Assumption 2 *Investment shocks ϵ_{jmt} 's are i.i.d. (across firms, markets and time periods) draws from a Type I extreme-value distribution.*

Assumption 3 *Incumbents have incomplete information about the profitability shocks of potential fiber entrants.*

Assumption 4 *Potential fiber entrant observe cable adoption decision before entry.*

Assumption 2 provides the distribution of the error draws. These draws are independent and identically distribution and this is used as a simplifying assumption. Assumption 3 states that incumbents do not observe profitability shocks of potential fiber entrants. This implies that cable firms make decisions based on expectations of what their competitors will do. Assumption 4 states that fiber firms observe cable adoption decision before they make their entry decision. This information assumption is made since cable incumbents' technology deployment is known to the potential fiber entrants³¹.

Assumption 5 *For each market m , there is a major cable incumbent and one potential entrant.*

Assumption 5 states that for each market there is a sequential game for a major incumbent and at least one potential fiber firm. This assumption is driven by the industry background since almost all markets have one potential fiber entrant. In addition, the major incumbent in this game is Time Warner.

7.1 State space

Firms' state space consists of three parts: exogenous market-level characteristics ($x_{mt}^c : m = 1, \dots, M$) (income and population density); market structure variables ($z_{mt}^c : m = 1, \dots, M$) (number of DSL firms, number of DOCSIS 3.0 firms and fiber firms); and third, whether the market is in the set of potential markets for the fiber firm. Cable incumbents consider these potential markets as markets under the threat of entry .

³⁰Note that there is no demand uncertainty in firms' decision in this model.

³¹Cable incumbents announce this information publicly.

Firm j 's payoff relevant state variables can be represented with the matrix $s_{jmt}^c = (x_{mt}^c, z_{mt}^c, \epsilon_{jmt}^c)$ and $s_{jmt}^f = (x_{mt}^f, z_{mt}^f, \epsilon_{jmt}^f)$ for a cable incumbent and a potential fiber entrant, respectively. In addition, the state matrix $s_{mt} = (s_{jmt}^c, s_{jmt}^f)$ describes the technology status of market m at time t .

7.2 Game Timing

I assume that the timing of the game is sequential and as follows:

Stage 1

In each market m , cable incumbents observe the state vector s_{mt} . Cable firms j choose whether to adopt the new technology in market m and take actions d_{jmt}^c . Cable has incomplete information about profitability shocks of fiber firms and, thus, can only predict the expected probability of fiber entry. A cable firm's expected profits if it adopts are:

$$\begin{aligned} \bar{\Pi}_m^c(d^c = 1|s_m) &= E\Pi_{1mt}^c(s_m) = \\ &E\left(\theta_{1cD}D_m + \theta_{1cDSL}n_{mDSL} + \theta_{1cF}n_{mf} + \mathcal{E}_m\right) - UC = \\ &\left(\theta_{1cD}D_m + \theta_{1cDSL}n_{mDSL} + \theta_{1cF}n_{mf} + \theta_{cF}*\Phi^f(\mathbf{s}_m|\mathbf{d}^c = \mathbf{1}) - UC\right) \quad (6) \end{aligned}$$

where $\mathcal{E}_m$ is an indicator function that takes value 1 if there is fiber entry, and $\Phi^f(s_m|d^c = 1)$ is the probability of fiber entry in the case of cable adoption. A cable firm's expected profits if it does not adopt are:

$$\begin{aligned} \bar{\Pi}_{mt}^c(d^c = 0|s_m) &= E\Pi_{0mt}^c(s_m) = \\ &E\left(\theta_{0cD}D_m + \theta_{0cDSL}n_{mDSL} + \theta_{0cF}n_{mf} + \mathcal{E}_m\right) = \\ &\left(\theta_{0cD}D_m + \theta_{0cDSL}n_{mDSL} + \theta_{0cF}n_{mf} + \theta_{cF}*\Phi^f(\mathbf{s}_m|\mathbf{d}^c = \mathbf{0})\right) \quad (7) \end{aligned}$$

where $\mathcal{E}_m$ is an indicator function that takes value 1 if there is fiber entry, and $\Phi^f(s_m|d^c)$ is the probability of fiber entry conditioned on cable adoption decision. θ_{cF} captures the competitive

effect of fiber entry on cable profits in the case of fiber entry.

In addition, the probability that cable firms adopt is³²:

$$\begin{aligned}\Phi^c(s_m) = P(\tilde{\Pi}^c(s_m) = P(\bar{\Pi}_{jm}^c(d=1|s_m) - \bar{\Pi}_{jm}^c(d=0|s_m) > \epsilon_m^c) \Rightarrow \\ P((\theta_{1cD} - \theta_{0cD})D_{mt} + (\theta_{1cDSL} - \theta_{0cDSL})n_{mDSL} + (\theta_{1cF} - \theta_{0cF})n_{mf} \\ + \theta_{cF} \underbrace{(\Phi^f(s_m|d^c=1) - \Phi^f(s_m|d^c=0))}_{\text{Deterrence effect}} - UC > \epsilon_m^c) \quad (8)\end{aligned}$$

Note that the term $\Phi^f(s_m|d^c=1) - \Phi^f(s_m|d^c=0)$ is the marginal effect on the fiber entry likelihood if cable incumbent adopts. Cable incumbent takes into account this deterring effect on fiber entry likelihood if it adopts. I set $\theta_{1cF} - \theta_{0cF} = \theta_{cF}$ which implies that current fiber firms and potential fiber entrants have the same effect on cable incumbent's profits. Assuming that the profit errors are drawn from a logit error distribution (Assumption 1), the probability that cable firm i will choose action j in an observable state s_m is:

$$\Phi^c(s_m) = \frac{\exp(\tilde{\Pi}_{jm}^c(d^c, s_m, \Phi^f(s_m|d_{jm}^c=0), \Phi^f(s_m|d_{jm}^c=1)))}{1 + \exp(\tilde{\Pi}_{jm}^c(d, s_m, \Phi^f(s_m|d_{jm}^c=0), \Phi^f(s_m|d_{jm}^c=1)))} \quad (9)$$

Stage 2

Potential fiber entrants observe cable firms' decision in market m, draw information shocks ϵ_{imt}^f and decide whether they should enter. Potential fiber entrants' payoffs depend on whether cable firm adopted in Stage 1. Entrants' i profits are

$$\Pi^f = \begin{cases} \theta_{fD}D_{mt} + \theta_{fDSL}n_{mDSL} + \theta_{fF}n_{mf} - EC + \epsilon_{mt}^f, & \mathbf{d}^c = \mathbf{0} \\ \theta_D D_{mt} + \theta_{fDSL}n_{mDSL} + \theta_{fF}n_{mf} + \theta_{fC} - EC + \epsilon_{mt}^f, & \mathbf{d}^c = \mathbf{1} \end{cases} \quad (10)$$

Also, the probability that potential entrants will choose to enter is:

$$\Phi^f(s_m|d_m^c) = \frac{\exp(\Pi_{jm}^f(s_m, d_m^c))}{1 + \exp(\Pi_{jm}^f(s_m, d_m^c))} \quad (11)$$

³²Note that only the difference of the above coefficients is identified.

Definition If $d_m^c = 1$, $\Pi_m^f < 0$ and $d_m^c = 0$, $\Pi_m^f > 0$ fiber entry is deterred in m .

The above definition implies that cable firms may have an incentive to adopt their strategic behavior to affect the probability of fiber entry. Entry is deterred in this case by cable incumbent's actions and not by demand itself. Since fiber firms observe cable's incumbent decision before they make their entry decision and investment is irreversible then the adoption decision creates a credible mechanism that post-entry profits will be lower than in the case of cable adoption.

Stage 3

In the last stage, firms receive payoffs in each local market m , and the market structure at time period t is determined. Note that since the cable firm enjoys higher profits in the case of no entry in stage 3, it has the incentive to adopt to deter fiber entry in that market.

7.3 Equilibrium

The cable incumbent has incomplete information about fiber firms' profitability shocks, so it calculates expected profits and post-entry equilibrium profits to determine whether or not to adopt. On the other hand, a potential fiber entrant observes the cable incumbent's decision before the entry decision. The cable incumbent's probability of adoption Φ directly determines the probability of fiber entry Φ^f .

Note that equations (9) and (11) can be interpreted as reaction functions. The equilibrium of the sequential game will be a vector p^* for each market m that describes each firm's optimal strategy conditional on other players' optimal decision:

$$p_m^* = (\Phi^c, \Phi^f)_m \quad (12)$$

This game is one of imperfect information since the incumbent does not observe fiber firms' profitability shocks. Also, I consider only pure strategy equilibria. There is always an equilibrium

in this game³³. The equilibrium concept here is a Subgame-Perfect Nash Equilibrium.

In this game, because of the order of the moves and the fact that fiber firms observe cable firms' action, entry can be deterred if the demand is unsustainable for a fiber entrant. This is what I consider a **Sequential Equilibrium** firms' strategies in which:

$$\tilde{\Pi}^c(d_m^{c*} = j, d_m^f, s_m) > \tilde{\Pi}_m^c(d^c = j', d_m^f, s_m), \quad \forall d_m^f, j \neq j', m, t \quad (13)$$

and

$$\Pi^f(d_m^{c*}, d_m^f = j, s_m) > \Pi_m^c(d_m^{c*}, d_m^f = j', s_m), \quad \forall d_m^{c*}, j \neq j', m, t \quad (14)$$

8 Identification of Strategic Effects

In this model, the potential fiber entrant decides whether to enter a market, and the cable incumbent decides whether to adopt. The cable incumbent makes decisions by using the direct effect of the adoption, as well as the indirect effect, which is the effect on their competitor's decision. I define deterrence strategy as the incumbent's motive to affect the entrant's profitability. The incumbent in this model can affect the entrant's profits by adopting the new technology in market m .

The sequential nature of the game allows for the cable firm to affect the potential fiber entrant's profits in the case of entry. Identification of the strategic strategies is based on the following argument: if we could predict cable incumbent's behavior with and without deterrence, we could also isolate the deterrence effect for each market.

Note that the spatial variation across markets identifies these effects since I observe one major incumbent (Time Warner), a different set of potential entrants (and mix of probability of entry) per market, and cross-section market heterogeneity.

The cable incumbent maximizes the following objective function:

³³For a discussion about sequential equilibria see Kreps and Wilson (1982) and Fudenberg and Tirole (1991).

$$\max_{\Phi^c} \bar{\Pi}^c = \Phi^f(\Pi^f(s_m, d^c)) \underbrace{\Pi^c(s_m, d^c | d^f = 1)}_{\text{Cable profits if fiber entry}} + (1 - \Phi^f(\Pi^f(s_m, d^c))) \underbrace{\Pi^c(s_m, d^c | d^f = 0)}_{\text{Cable profits if no fiber entry}} \quad (15)$$

Profit maximization implies:

$$\begin{aligned} \frac{\partial \bar{\Pi}}{\partial \Phi^c} = & \Phi^f(\Pi^f(s_m, d^c)) \frac{\partial \Pi^c(s_m, d^c | d^f = 1)}{\partial \Phi^c} + (1 - \Phi^f(\Pi^f(s_m, d^c))) \frac{\partial \Pi^c(s_m, d^c | d^f = 0)}{\partial \Phi^c} \\ & + \underbrace{(\Pi^c(s_m, d^c | d^f = 1) - \Pi^c(s_m, d^c | d^f = 0)) \frac{\partial \Phi^f(s_m, d^c)}{\partial \Phi^c}}_{\text{Deterrence effect}} \end{aligned} \quad (16)$$

The first line of equation (18) corresponds to the direct effect of adoption, while the last term is the indirect effect. In addition, we should expect this term to be positive and to lead to a higher level of investment.

Note that in the case of no deterrence effects, the last term that measures deterrence will be zero. This is equivalent to setting the last term in equation (19) as zero. If the last term of equation (19) is zero, this implies that the cable firm makes adoption decisions without adjusting its strategy to deter fiber entry.

Thus, I focus on markets where Time Warner is the major incumbent and isolate the deterrence effect for each market using a different mix of demand characteristics and fiber entry likelihood.

9 Estimation and Results

In this section, I describe the estimation method and the results from the structural model. I solve the above game backwards by substituting (11) in (9) for each market m . For a random draw of the parameter vector θ I calculate potential fiber firms' profits in the case of cable adoption or no adoption. Then, I calculate probability of fiber entry Φ_m for $d_m^c = 0$ and $d_m^c = 1$ according to (11).

Then, I substitute these values in equation (8) and receive the probability of cable adoption (9). Since Φ_m^f is function of Φ_m^c , I use a contraction mapping algorithm to find a fixed point for the probability of cable adoption Φ_m^c . Then, from equations (9) and (11) I nest the solutions to a maximum likelihood routine (MLE) to receive the estimated parameter vector $\hat{\theta}$. The likelihood

function is then:

$$L = \prod_m (\Phi_m^c)^{d_m^c} (1 - \Phi_m^c)^{1-d_m^c} \\ * \prod_m (\Phi_m^f(d^c = 0))^{d_m^f} (1 - \Phi_m^f(d^c = 0))^{(1-d_m^f)} \\ * \prod_m (\Phi_m^f(d^c = 1))^{d_m^f} (1 - \Phi_m^f(d^c = 1))^{(1-d_m^f)} \quad (17)$$

where c and f are cable and fiber firms. The likelihood function uses probability of adoption from equation (9) and fiber entry propability from equation (11) in the case of cable adoption or not.

Table 6 shows the results of the above game³⁴. The results indicate a negative effect on cable incumbent's profits from a fiber entrant (-0.4966) and a negative effect from cable adoption on fiber entry likelihood (-2.928). In addition, I receive the adoption (1.2095) and entry cost (6.4412).

CABLE	Log (Pop density _m)	-0.2362*** (0.0165)
	Log(Agg hh inc)	0.0429*** (0.0147)
	DSL firms _m	-1.8858*** (0.0978)
	Fiber firms _m	-0.4966*** (0.0391)
	Adoption cost	1.2095*** (0.2678)
FIBER	Log(Pop density _m)	0.4518*** (0.020)
	Log(Agg hh inc)	-0.1099*** (0.01)
	DSL firms _m	3.0224*** (0.095)
	Cable adoption _m	-2.9280*** (0.2953)
	Fiber firms _m	1.8129*** (0.033)
	Entry cost	6.4412*** (0.3739)
Number of obs.		39,157
$\mathcal{L}$		10,721

* p < 0.05, ** p < 0.01, *** p < 0.001

Table 6: Structural parameter estimates.

³⁴In the Appendix, Section A.5, I provide some Monte Carlo simulations.

10 Model fit

In this section, I present how the model fits the data. First, I present the cable adoption and entry rates in Tables 7-8 for different demand characteristics' quartiles. In particular, I report the number of local markets with cable adoption and fiber entry for various demand levels.

In Table 7, I illustrate population density quartiles in the data and model's predictions. In general, the model matches the data well with some variation for cable adoption. In Table 8, I illustrate aggregate income quartiles in which the model fits the data as well. In general, the models fits the data quite well.

Population density		25%	50%	75%	100%
<i>Cable adoption</i>	Data	416	279	187	172
	Model	338	243	245	215
<i>Fiber Entry</i>	Data	400	591	595	900
	Model	369	576	576	952

Table 7: Model fit: population density quartiles and number of markets with cable adoption and fiber entry.

Aggregate Income		25%	50%	75%	100%
<i>Cable adoption</i>	Data	698	358	5	0
	Model	664	287	47	51
<i>Fiber Entry</i>	Data	167	305	930	1,101
	Model	221	333	839	1,117

Table 8: Model fit: aggregate income quartiles and number of markets with cable adoption and fiber entry.

11 Counterfactuals

11.1 No Deterrence

In the first counterfactual, I use the estimates of the above game but remove the deterrence effect. Thus, I allow firms to compete in technology deployment but remove the cable incumbent's

incentive to deter entry. In other words, the cable incumbent is precommitted to investment strategies that do not affect fiber's entry decision pre-entry. In other words, I examine deviation from incumbent's optimal strategy with deterrence.

	Cable Adoption	Fiber Entry
Observed rates (<i>Baseline</i>)	1,062	2,542
No deterrence	891 -16%	2,860 +12.5%

Table 9: Counterfactual scenario: No Deterrence.

Thus, in the first counterfactual, I use the estimates from the above game but set the last term in equation (8) as zero:

$$\Phi^f(s_m|d^c = 1) - \Phi^f(s_m|d^c = 0) \longrightarrow 0 \quad (18)$$

Table 9 presents the results of this exercise. If we remove the deterrence effect, we expect a drop of almost 16% in cable adoption rates across markets and 12.5% higher fiber entry across markets.

This counterfactual indicates that cable firms invest more than we would expect without the entry deterrence effect. This strategy is successful since it reduces the entry rates significantly across markets. It is not surprising that the rate of excessive cable adoption is more than the increase of fiber entry. This implies that the cable incumbent cannot deter entry anywhere. In addition, note that this successful deterring strategy across local markets results in technology variation since there is expansion of DOCSIS 3.0 but optical fiber is deterred.

Note that this counterfactual has an additional interpretation. If fiber firms credibly announce entry irrespective of what the cable incumbent decides, then the cable incumbent may not have the incentive to adjust their adoption strategy to deter entry.

11.2 Subsidies only to Small Markets

	Cable Adoption	Fiber Entry
Observed rates (<i>Baseline</i>)	339	73
Subsidies to Cable firms	993	35 (-52%)
Subsidies to Fiber firms	330 (-2%)	693

Table 10: Counterfactual scenario: Subsidies to markets in the 10% of population density distribution. Obs. is a market/t. Firms are subsidized with the whole amount of investment.

In this counterfactual, I use the estimated parameters and assume that the state government budget subsidizes ISPs in markets which belong to the 10% of markets of population density and under the threat of fiber entry. NY State has an extensive subsidy program that funds local markets with little or no broadband. New York State funds cable or fiber firms to offer service to unserved areas³⁵ through the NY Broadband Grant Program.

Table 10 shows the results, which indicate that a subsidy for the whole amount of the incumbent's investment reduces the fiber entry rate in these market by over 50%. On the other hand, if the fiber firms are subsidized in these markets, fiber entry increases significantly, while cable adoption rates drop by 2%.

These results are important for three main reasons. First, they show that there are heterogeneous effects when the policy maker chooses who to fund to offer broadband service and where. Second, if subsidies to cable incumbents reduce the fiber entry rates in these low-demand markets, then the policy maker should take into account these competitive effects in determining the optimal subsidy policy. Third, subsidizing fiber firms also increases cable adoption through the competitive effect of deterrence strategies.

³⁵ An unserved area is defined as an area where broadband service is not available from a wireline or wireless facilities-based provider at advertised speeds equal to or higher than 25 Mbps download.

11.3 Statewide Fiber Entry

In this counterfactual, I consider the effect on technology diffusion and market structure if fiber firms are allowed to enter anywhere in the state. New York State restricts where fiber potential entrants can actually enter. In particular, fiber entry depends on negotiation with the local authorities which increases the cost of entry significantly or make it impossible. This policy alters fiber firms' choice set and expands threat of entry for cable incumbents. On the contrary, there are US states that a statewide permit allows fiber to enter anywhere in the state (e.g. Texas)³⁶. Note that this counterfactual is equivalent with a policy that removes any local entry barriers that make entry cost infinite.

In this counterfactual, I use the estimates from Section 9 but allow the five potential fiber firms to enter in all local markets in the state and examine how it affects cable adoption decision and fiber entry. In addition, I include the indirect effect on cable incumbents' profits. I assume that fiber firms make independent entry decisions and thus, they do not take account other potential entrants' decisions. Table 11 illustrates the results of this exercise.

	Cable Adoption	Fiber Entry
Observed rates (<i>Baseline</i>)	2,390	3,645
Statewide Entry	1,854 -22.4%	4,755 +30.4%

Table 11: Counterfactual scenario: Statewide Fiber Entry. I assume fiber firms are symmetrical and each market has 5 potential entrants.

A statewide license for potential fiber entrants has significant results on market structure. First, it alters significantly both cable adoption and fiber entry rates across local markets. In particular cable now offer DOCSIS 3.0 in 22% less markets while fiber entry rate increases by 30%. Second, this implies that a way for policy makers to mitigate deterrence effects is to alleviate local barriers. The intuition for these effects is that cable firms now face larger entry threat so their incentive to deter entry becomes significantly lower. This exercise quantifies this effect.

³⁶For instance, Google Fiber negotiates entry and access to utility poles with city officials in states where there is no statewide license.

12 Conclusion and Future Work

In this paper, I combine data sources on the broadband industry and introduce a model of strategic investment. I provide evidence of strategic investment by cable incumbents to deter fiber entry. To the best of my knowledge, this is the first study to examine cable incumbents' excessive investment, which has a deterring effect on potential fiber firms entry.

The results from the structural model indicate that in the absence of deterrence strategies, we should have observed 16% lower cable adoption rate across local markets and 12% more fiber entry. In addition, policies that subsidize fiber firms in small markets are more effective in their competition effects than subsidies to cable firms. In particular, subsidies to cable incumbents in less attractive markets make the above effects stronger. In particular, I find that subsidies to cable incumbents in small markets can reduce fiber entry by 50%. On the contrary, subsidies to fiber firms do not affect cable adoption significantly. Furthermore, I find that statewide entry increase both cable adoption rates and fiber entry.

This paper adds to the literature new evidence on why there may be less fiber entry rate and slower spatial diffusion of new technologies across local markets. This result is crucial from a policy perspective and is related to how technology decisions are driven by competitive effects and, in particular, the threat of entry. This paper also highlights why demand may be unsustainable for new networks in the case of technology adoption by incumbents. In addition, the results indicate that policy makers should take into account these deterrence strategies when they decide where to subsidize incumbents to adopt faster.

There are some issues not discussed in this article that may be incorporated in future work. First, I do not include unobserved market heterogeneity. This factor may play some role in how attractive a market is to cable and fiber ISPs—possibly in different ways. This unobserved factor may be private information for each firm and it may work as a signaling mechanism. Second, data limitations do not allow to examine what happens post-entry and how the cable incumbents adjust their strategy. Third, future work could quantify the welfare losses of these strategies by incorporating demand estimation for higher speeds but perhaps also preferences for technologies. In addition, there may be some network effects in adopting regionally. This is related to cost benefits from adopting or entering regionally. Finally, future work would examine the effect of these strategies on the diffusion of related industries.

Appendix

A1. Data Construction

This section discusses some additional details about constructing the dataset. The level of these data is at the block group level.

A1.1 Broadband Map Data

The first part of the dataset is compiled by the U.S. Dept of Commerce, the National Telecommunications and Information Administration, and the State Broadband Initiative for the period June 2010 until December 2014 every six months. For this paper, I use data for the period June 2011 until December 2013 for various reasons³⁷ for both wireless and wireline broadband.

In this study, I focus only on wireline broadband. This dataset is compiled at the census block group level, which is the lowest possible geographical level (smaller than county and census tract). The dataset provides information about the speed provided by broadband providers, and, the technology used. In addition, it provides the name of the provider, the holding company name, the unique identification number per firm and holding company, state, full block group number, maximum download advertised speed, typical download speed, maximum upload advertised speed, and typical upload speed.

The technologies in the dataset include: Cable modem DOCSIS 3.0, DOCSIS 2.0 or other, Optical Fiber, Asymmetric DSL, Symmetric DSL, Satellite, and Electric Power Line. I keep observations only for Cable modem 3.0 or other, Optical fiber and Asymmetric DSL since these are the dominant technologies in the industry. In addition, the industry does not exhibit significant cross-technology firm variation. This means that firms mostly provide a technology to the end user and make upgrades to their existing network.

I aggregate provider information at the block group level. This is a level above block but lower than census tract. More specifically, I keep track of which technologies these firms offer in a specific block group.

³⁷I do not use data before June 2011 because census block group identification numbers use US Census 2000 classification, while the later versions use census block group identification numbers from US Census 2010 classification. I do not use later versions of the dataset since the technology adoption I examine in this paper had already occurred.

A1.2 Potential Markets

I consider five fiber firms as potential entrants. These firms account for more than 90% of total fiber entry observations. For each firm, I describe the data collection process and its potential markets. These data are at the county level. For the period 2011-2013, there is no time variation in the potential markets.

Nicholville Telephone Company

I use internet archives (i.e., Wayback Machine) from 2011 to 2014 to check the provider's operation area. The potential markets for this fiber provider are all markets included in St. Lawrence County.

Northland Communications

This firm is a central NY state provider. I use internet archives (i.e., Wayback Machine) from 2011 to 2014 to check the provider's operation area. The provider issued announcements about service offers for various areas. The potential markets for this fiber provider are all markets in the following counties: Cortland County, Madison County, Oneida County and Onondaga County.

Trumansburg Telephone Company

I use internet archives (i.e., Wayback Machine) to check the provider's operation area. The provider issued a map of the area serviced. I used maps between 2011 and 2016 to check the service areas. The potential markets for this fiber provider are all markets in the following counties: Allegany County, Cayuga County, Chemung County, Cortland County, Erie County, Monroe County, Onondaga County, Ontario County, Schuyler County, Seneca County, Steuben County, Tioga County and Tompkins County.

Verizon

Verizon is the largest DSL provider in the state. Between 2004 and 2008, it rolled out Verizon Fios in a significant number of markets within the state. After 2011, the firm re-initiated fiber rollout in new markets. For Verizon, I use franchise agreements signed with the state's cities for fiber rollout—in particular, a 2009 agreement with the New York City. The potential markets for this fiber provider are all markets in the following counties: New York County, Suffolk County, Queens County, Dutchess County, Nassau County and Kings County.

Lightower

Lightower is a significant fiber provider offering service mainly to businesses, government, schools and hospitals. I use internet archives (i.e., Wayback Machine) to access the network map and ser-

vice locations (city level). The potential markets for this fiber provider are all markets in the following counties: Albany County, Bronx County, Kings County, Nassau County, New York County, Queens County, Richmond County, Suffolk County and Westchester County.

A1.3 Demographics

I match census block groups with demographic information at the census block group level from the American Community Survey. The variables I use are population density and aggregate household income. Since the Broadband Map is published at six-month intervals to get a population and income estimate, I calculate the mean population and income growth by year and take an estimate for the June population and income based on the population of the last year.

A2. Alternative Potential Entry definition-Neighboring markets

In this section, I use an alternative potential entry definition by allowing fiber firms to enter neighboring markets. There are technological reasons (as described in Section 2) that may make fiber entry less costly for fiber firms if they already have a presence in neighboring markets.

In Table 11, I allow fiber firms to enter any local market in the state. I use logit specifications for fiber entry. A firm is a potential entrant in a market if it offers service in a neighboring market. The results indicate that there is a negative effect on fiber's entry if the cable incumbent adopts in all specifications.

In Table 12, I consider entry in neighboring markets of 20km from a prior market. Now, the Time Warner adoption effect is negative in any specification. These effects are smaller than those in Table 3 indicating that entry in neighboring markets is less important than the potential market definition I used throughout the article.

	(1)	(2)	(3)
P(Fiber entry_{jmt})	Logit	Logit	Logit
Log(Pop density _{mt})	0.104*** (0.01)	0.115*** (0.01)	0.038* (0.02)
Log(Agg hh inc) _{mt}	0.260*** (0.03)	0.244*** (0.03)	0.206*** (0.03)
DSL firms _{mt}	0.128** (0.04)	0.252*** (0.04)	0.230*** (0.06)
Fiber firms _{mt}	0.016 (0.02)	0.082*** (0.02)	0.092*** (0.02)
Time Warner 3.0 _{mt}	0.278** (0.10)	-0.720*** (0.11)	-0.165 (0.13)
Constant	-8.965*** (0.49)	-8.850*** (0.48)	-7.495*** (0.82)
Time FE		Yes	Yes
Firm/County FE			Yes
Number of obs.	448,608	448,608	173,848
R-squared	0.015	0.106	0.321

* p < 0.05, ** p < 0.01, *** p < 0.001

Table 12: Determinants of fiber entry. Firms' choice set includes all markets in the state. Marginal effects from the logit specification are reported. Standard errors are clustered at the census tract level.

	(1)	(2)	(3)
P(Fiber entry_{jmt})	Logit	Logit	Logit
Log(Pop density _{mt})	-0.057* (0.03)	-0.055* (0.03)	0.023 (0.04)
Log(Agg hh inc) _{mt}	0.067 (0.06)	0.055 (0.06)	0.160* (0.06)
DSL firms _{mt}	0.062 (0.12)	0.039 (0.12)	0.104 (0.14)
Fiber firms _{mt}	-0.629*** (0.10)	-0.525*** (0.11)	-0.648*** (0.13)
Time Warner 3.0 _{mt}	-1.434*** (0.24)	-1.502*** (0.23)	-0.322 (0.28)
Constant	-3.986*** (1.18)	-3.675** (1.16)	-5.929*** (1.28)
Time FE		Yes	Yes
Firm/County FE			Yes
Number of obs.	69,748	69,748	42,812
R-squared	0.033	0.056	0.257

* p < 0.05, ** p < 0.01, *** p < 0.001

Table 13: Determinants of fiber entry. Firms' choice set includes all markets in the state. Marginal effects from the logit specification are reported. Standard errors are clustered at the census tract level.

A3. Cable adoption and potential entry

First stage: Fiber entry

P(Fiber entry_{jmt})	Marginal Effect
Log(Pop density _{mt})	0.004*** (0.00)
Log(Agg hh inc) _{mt}	-0.003** (0.00)
DSL firms _{mt}	0.050** (0.00)
Fiber firms _{mt}	0.029*** (0.00)
Time Warner 3.0 _{mt}	-0.023 (0.01)
Time FE	Yes
Firm/County FE	Yes
Number of obs.	26,346
R-squared	0.508

* p < 0.05, ** p < 0.01, *** p < 0.001

Table 14: Determinants of fiber entry. Markets that are under threat of fiber entry and in which Time Warner is the major cable incumbent. Marginal effects from the logit specification are reported.

In the first stage of Ellison and Ellison (2011) application, I use a logit specification of fiber entry on exogenous market characteristics. I report the marginal effects of this specification in Table 14. From this specification, I receive the predicted fiber entry likelihood and use it as a explanatory variable for cable adoption decision in specification (3).

A4. Game Description

In the above tree, I describe the sequential game. In this game, deterrence occurs when cable adopts and fiber entrant's post-entry profits are $\Pi_{f1} < 0$. In the case of no deterrence, the cable incumbent should adopt and the potential fiber entrant enters.

A5. Simulation Draws

		Estimates	n=5	n=20	n=50
CABLE	Log(Pop density _m)	-0.2362 (0.0165)	-0.2418 (0.0165)	-0.2399 (0.0164)	-0.2366 (0.0164)
	Log(agg hh inc _m)	0.0429 (0.0147)	0.0537 (0.0149)	0.0491 (0.0146)	0.0431 (0.0151)
	DSL firms _m	-1.8858 (0.0978)	-1.9118 (0.0991)	-1.8930 (0.0980)	-1.8898 (0.0984)
	Fiber firms _m	-0.4966 (0.0391)	-0.4614 (0.0395)	-0.4794 (0.0395)	-0.4891 (0.0394)
	Adoption cost	1.2095 (0.2678)	1.2920 (0.2713)	1.2771 (0.2668)	1.2644 (0.2754)
	Log(Pop density _m)	0.4518 (0.0209)	0.4407 (0.0207)	0.4546 (0.0210)	0.4512 (0.0209)
	Log(agg hh inc _m)	-0.1099 (0.0100)	-0.1073 (0.0100)	-0.1129 (0.0100)	-0.1107 (0.0100)
FIBER	DSL firms _m	3.0224 (0.0945)	3.0297 (0.0948)	3.0543 (0.0959)	3.0595 (0.0957)
	Cable adoption _m	-2.9280 (0.2953)	-3.0232 (0.3124)	-3.0107 (0.3120)	-2.9195 (0.3194)
	Fiber firms _m	1.8129 (0.0333)	1.8067 (0.0333)	1.8148 (0.0335)	1.8200 (0.0335)
	Entry cost	6.4412 (0.3739)	6.5400 (0.3922)	6.4928 (0.3910)	6.4244 (0.3980)
	Cable adoption rate	1,062	1,030	1,053	1,066
	Fiber entry rate	2,542	2,530	2,542	2,533

Table 15: Monte Carlo Simulations.

In this section, I provide some Monte Carlo simulations for the entry model using the following process: I receive the structural estimates, exogenous market characteristics and error terms from a logistic distribution $\Lambda(0, 1)$ to generate cable and fiber firms' choices in the set of potential markets for a number of draws n .

The results of the simulation draws are shown in Table 15. For each sample of size n , I report the mean of the number of draws. In general, the coefficients collapse to their estimated values as n increases.

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