THE MARKET STRUCTURE OF BROADBAND TELECOMMUNICATIONS

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Abstract

The recent popularity of the Internet and World Wide Web with both consumers and firms suggests that markets requiring telecommunications networks capable of interactive high-speed data transfers may emerge in the near future. In the past, virtually all networks, communications and others, have been subject to regulation by government agencies, and subject to various restrictions. Two reasons advanced for this market intervention are (i) the belief that such networks constitute a natural monopoly for which competition is not feasible, and (ii) to achieve "universal service," in which all (or most) citizens have access to network services. In this paper, we develop a model and estimate it using engineering data which tests whether or not these two hypotheses are like to obtain for interactive broadband networks. We find that some form of imperfect competition is likely to emerge for demand levels approaching that of today's cable TV. Further, in a dynamic model of competition, a "first mover" is likely to accelerate network investment in order to preempt competitors; a firm using this preemptive strategy will grow its network faster than a monopolist and (in some cases) faster than the socially optimal network deployment.

Keywords: economics of information, economics of networks, broadband, Internet

JEL classifications: L13, L51, L96

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1. Introduction

The recent popularity of the Internet and World Wide Web with both consumers and firms suggests that markets requiring telecommunications networks capable of interactive high-speed data transfers may emerge in the near future. Annual growth of Internet hosts, for example, has been a phenomenal 25% for the last decade, and appears to have increased in the last several years. Although the Internet was designed and developed by academic researchers, principally in the physical sciences, the advent of the World Wide Web and browser technology in the early 1990s has fostered growth outside the academic community. In mid-1994, the number of commercial sites (the "com" domain) exceeded the number of educational sites (the "edu" domain) for the first time, indicating a strong commercial interest in reaching this new audience of consumers (rather than researchers). In addition, many see this form of communication as a critical input for primary and secondary education. It is already an important function of both public and private libraries in the US, and promises to be more important in the future, as archived material migrates from the printed page to electronic storage.

The core of this activity is the transmission of graphical information between remote hosts and end-users interactively, so that large amounts of data (i.e., graphical) must be made available quickly (i.e., interactively[1]). To accomplish this, two things are required: (i) a public network using shared facilities (the Internet) capable of data transfer rates considerably greater than traditional telephone networks; and (ii) access facilities to connect individual customers to the public network, which also must be capable of high data transfer rates. These transfer rates are expressed in bits/second, with end-to-end telephone service using a transfer rate of approximately 5-10 Kbps and full-motion television (for example) using a transfer rate of at least 10 Mbps. The telephone network is thus a "narrowband" facility, while cable television (for example) is a "broadband" facility, representing the bandwidth required to transmit the electronic signal that carries the information.

Universities and many firms provide broadband access to the Internet, so connections for their users are usually quite speedy.[2] Access from other points, such as a customer's home, is usually accomplished over a telephone line, which is narrowband.[3] This bandwidth limitation of telephone access severely limits the content available to many customers. For example, video clips, animated websites, even high-quality photos often create very long delays while megabytes of data trickle through the telephone line. The ability to create content that many customers would like to access has outstripped the ability of narrowband access connections to deliver this content interactively.

Whether or not the forecasted demand for the interactive delivery of graphic and video data actually materializes is hotly debated. Many believe that the current growth in Internet and the World Wide Web is merely a fad, and will fade when customers tire of long waits for useless information. Others believe that today's Internet is merely the leading edge of a ubiquitous, worldwide demand for content-rich interactions, including two-way video, online game-playing, and other bandwidth-intensive activities. Until such systems become widely available, actual demand will not be known, or knowable. However the initial sales of high-speed Internet access products such as AT&T's @Home service suggest that such customer demand does exist for a non-trivial fraction of the population. Companies large and small are investing based on this promise, indicating that many investors are willing to bet on the realization of this demand.

Overcoming current bandwidth limitations requires substantial infrastructure investments. New transmission facilities and server capacity will be required in the public network, although this is not the focus of this paper. Perhaps more critically, access to the home and small business will be upgraded from the current narrowband telephone connection to a broadband distribution network. While such distribution networks are likely to evolve from today's telephone, satellite, or cable networks, they are still likely to involve the investment of tens, perhaps hundreds, of billions of dollars to reach a majority of US households and small businesses. The deployment of broadband networks may be as significant as the deployment of telephone networks in the early part of the twentieth century or of cable systems in the 1970s and 1980s.

Virtually all public networks in the US, communications and others, are subject to regulation by government agencies.[4] This regulation is usually quite intrusive, mandating the specific terms of trade (price, quality, what services are offered, to whom service must be available, etc.) between the network operator, its customers, and often other firms with which the operator does business. Two economic reasons[5] advanced for this market intervention are (i) the belief that such networks constitute a natural monopoly for which competition is not feasible and regulation is therefore necessary to control monopoly power, and (ii) to achieve "universal service," in which all (or most) citizens have low-cost access to the services of the network.[6]

In this paper, we take no normative position regarding regulation or the lack thereof in the provision of access broadband networks to households and businesses. We investigate a narrow set of positive issues: (i) the "natural monopoly" question: is it likely that an unregulated market would result in only one supplier? And (ii) how many households would have access to broadband services in an unregulated market? While these questions are certainly relevant to the issue of whether regulation is appropriate for this emerging industry,[7] they are by no means dispositive. Other political, technical, social and economic issues, not discussed in this paper, will no doubt also weigh in the political decision to regulate or not.

In this paper, we develop a market model of competition among broadband access providers who must build networks in a (stylized) metropolitan area in order to offer service. The model is calibrated using engineering data for hybrid fiber-coax (HFC) networks.[8,9] We consider three scenarios: (i) a static model, in which demand is fixed, firms decide to enter, choose the scope of their network, build capacity and offer service; (ii) a static model in which firms are free to enter as in (i) but are required as a condition of franchise to build a network that would serve 95% of the metro area population ("universal service" regime); and (iii) a dynamic model, in which demand is growing and firms can make strategic network investments in order to preempt a competitor and therefore gain or maintain a dominant market position.

There are almost no broadband systems in mature markets; consequently, our models and data do not pass the rigorous test of econometric evidence, since no such evidence exists. Our conclusions, therefore, are at best merely indicative, perhaps no better than informed guesses. However, the discipline of model building and data calibration may permit us to emphasize "informed" over "guesses," and the results worthy of some attention.

We find in the static scenario that:

(i) broadband deployment is profitable in both high-density and low-density cities at demand levels about 7%-20% higher than today's demand levels.

(ii) market equilibrium is asymmetric in network size; the firm with the largest network is more profitable than firms with smaller competitive networks;

(iii) facilities-based competition is feasible at demand levels about 70% greater than today's demand levels. In high-density cities, broadband is available to all at demand levels 50% greater than today's demand; a competitive service is available to all at demand levels 100% greater than today's. In low-density cities, broadband is available to all at a demand level 130% greater than today's; at this level, competition is available to 75% of the metro area households.

(iv) the universal service regime leads to fewer competitors in the market at some demand levels. This effect is fairly small in high-density cities and somewhat larger for low-density cities. However, it is not dramatic enough to foreclose entirely facilities-based competition at some demand levels.

We find in the dynamic scenario:

(i) the first mover firm always builds a larger network than is the case in the static model in order to preempt investment by entrants;

(ii) entry still occurs at greater demand levels; preemption by a first mover does not foreclose entry; rather it guarantees the first mover the advantage of the larger (and more profitable) network;

(iii) while demand is growing, preemption results in a larger network than short-run profit maximization, and can lead to a larger network than that which would be socially optimal.

In Section 2, the cost structure of communications networks is discussed; in Section 3, the static market model is developed, and equilibrium conditions derived. In Section 4, engineering estmates of cost and the parametric estimates of demand are used in the model to derive expected market outcomes for the static model. In Section 5, the dynamic strategic investment model is developed, the equilibrium is derived, and parameterized market outcomes are computed using the cost and demand. Section 6 summarizes the conclusions that follow from the analysis.

2. The Cost Structure of Broadband Networks

The Cost Structure of Broadband Infrastructure There are generally three types of costs associated with communications systems: (i) a cost per unit of usage[10] (such as a minute or a packet); (ii) a cost per user (such as the cost of the access connection); and (iii) a cost per potential user of service availability (such as the cost to extend, say, a fiber optic line down a street). The latter two costs are somewhat different than might occur in other industries, although they are typical of infrastructure systems. For example, a provider of fiber services would have to construct its network of fiber lines underneath the streets (or on telephone poles), and its choice of where to build such lines would limit its market to only those homes and businesses which are passed by their fiber lines. However, simply laying the cable does not connect the homes so passed. If a home or business wished to be connected, additional capacity in the form of electronic gear at each end of the fiber connection (at the customer's location and the communication firm's location) must be installed to actually utilize the fiber for transmission purposes.[11] Thus, the firm must make three capacity decisions: (i) how much common network capacity to install (to handle actual usage); (ii) how much access connection capacity to install (to handle the number of customers); and (iii) how big a network to build, and where to build it (i.e., which geographic markets it wishes to serve).

It is this geographic network decision that makes broadband networks, indeed most network infrastructure, a unique problem.[12] Once a network is built with a specific geographic scope, then the network can be used to provide service to *everyone* within this market region, and *no one* outside this region. In order to serve a single customer in a neighborhood (say, a city block), a network service provider must provide a facility (say, a fiber optic cable passing under the street) that is capable of serving *all* the households in that neighborhood. It is this property of network investment that leads to the unusual market equilibrium results of Section 3. Further, this network investment is fully sunk, in that this network segment cannot be used to serve any other demand other than that specific neighborhood. It is this property that leads to the preemptive dynamic equilibrium results of Section 5.

The Cost Structure of Broadband Content Provision Earlier communications networks also had the infrastructure cost structure discussed above. But they also had an additional property that users could not readily interconnect between competing networks. In cable television, the result is that users can only view a select group of channels that are determined by the cable company. More significantly, in early telephone competition the lack of interconnection meant that users who subscribed to a Bell telephone company could not place a call to subscribers of an independent telephone company. Thus each telephone company tried to build up as large a subscriber base as possible in order to create network externalities, and many businesses needed to maintain two subscriptions in order to receive calls from all of their customers. Mueller (1997) makes the case that the term "universal service" originally meant "universal interconnection," and that the formation of the Bell monopoly was in part justified on the basis that all telephone subscribers should be able to call one another.

By contrast, the popularity of the Internet is based on a common set of protocols that allow data to be transmitted over a variety of networks and viewed on a variety of platforms. That means that interconnection of broadband access networks is to some degree a foregone conclusion, and there may not be the same firm-specific network externalities as there were in early telephone competition.[13] Likewise, interconnectivity is likely to reduce the ability of broadband providers to select and edit content relative to current cable TV providers. For these reasons, this paper models facilities-based infrastructure competition only, and assumes that all infrastructure competitors can provide access to identical content.[14]

The Technology of Broadband Infrastructure Recently a great deal of attention has focused on what technology will be used to provide broadband access, with hybrid fiber-coax (HFC, also called cable modem) and DSL (over telephone lines) the leading contenders. At this time, HFC,which consists of a fiber-optic network connected to homes and businesses using coaxial cable, is the only contender which can provide true broadband (up to 10 Mbps) at reasonable cost. While this bandwidth is subject to congestion as additional users access the system, the technology is scaleable so that more fiber optic lines can be added to increase capacity. HFC can be installed as an upgrade to existing cable television networks, so in most areas the initial HFC provider will be the incumbent cable company. Because two-way HFC upgrades require very extensive construction on the network, we do not expect incumbents to have significant cost advantages over possible new entrants in this industry.

The other available broadband technologies currently cannot offer the same bandwidth as HFC at a comparable cost (Omoigui, Sirbu, Eldering & Himayat, 1996). Digital subscriber line (DSL, an upgrade to traditional twisted-pair copper telephone lines) only offers 640 Kbps bandwidth at prices comparable to HFC cable modems, and direct broadcast satellite (DBS) typically provide around 400 Kbps one-way bandwidth, again at higher prices than HFC.[15] There are some promising new technologies, including fixed-base wireless and low-orbit satellite, that may be able to challenge HFC in the future, but their prospects are very uncertain for now.

Because of these advantages of HFC, and because there seems to be an emerging consensus that HFC is the preeminent broadband access technology,[16] we have focused on HFC deployment in this paper. While there is likely to be a transitional period during which other "medium-bandwidth" technologies siphon off some demand from HFC, we believe that in the long run HFC networks will dominate the market structure of the broadband access industry

3. A Model of Competition in Communications Networks

The model is formulated for the first scenario of static competition. Where the structure of the universal service scenario differs, the differences are described. Firms compete to serve consumers who live in a linear city. They play a three-stage static game with complete information.

Market Geography There are M households in a linear city, defined on the interval $[0,M]$, indexed by increasing distance from the city center. We can think of this interval as representing a metropolitan area, with household number 1 living at the very center of the city and household M living far out in the rural hinterlands. Associated with each household is a density attribute that describes the household's spatial setting. The density attribute, which we take to be the population density in the immediate area of the household, proxies for such data as the distance to the nearest neighbor, lot size, single-family versus multiple-family dwelling, etc. Let the density attribute for household $m \in [0,M]$ be given by $d(m/M)$. We assume this function is monotonically decreasing in m, since houses tend to be situated further apart farther out from the city center.[17] This geographical setting is depicted in Figure 1.

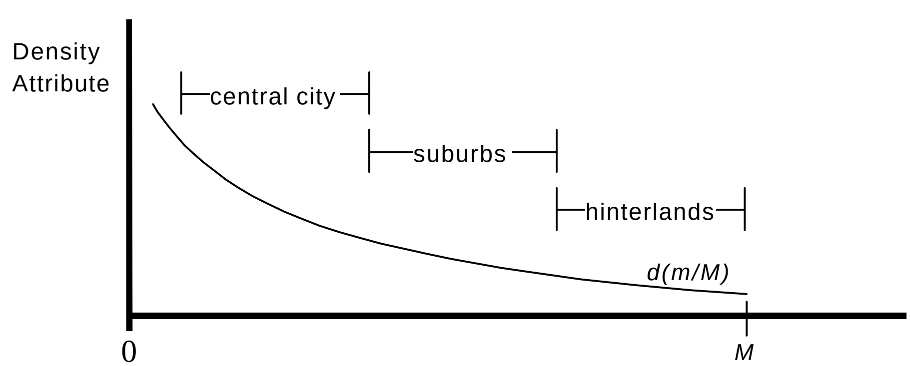


Figure 1: Households in the Interval [0,*M*]

We assume all households in the city have identical preferences for broadband services; households only differ in their density attribute.[18]

The Game A large number of identical firms may offer broadband access services in this metropolitan area. They play a three-stage game, the timing of which is shown in Figure 2. The results of each stage are revealed to all.

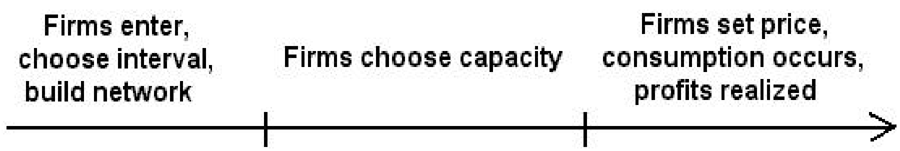


Figure 2 - Timing of Network Competition Game

In the first stage, identical firms decide whether and where to build a network; we assume without loss of generality that each firm *i* that enters selects a single interval $[h_i,H_i]$. Firms move sequentially in some order; we index firms according to the order in which they move. Let $F(h)$ be the cost of constructing a fiber network from the city center to the household *h* (i.e., the interval $[0,h]$), assuming $F' > 0, F'' > 0$.[19] Then the cost to build the network to cover the interval $[h,H]$ is $F(H) - F(h)$. This choice determines the market from which each firm draws customers in the final stage. At the end of the stage, all network construction is completed and is common knowledge.

The interval choices of the fiber firms may overlap, so that more fiber firms serve some areas than others. For example, if there were two fiber firms, it might be that $h_1<h_2<H_1<H_2$. This situation is illustrated in Figure 3:

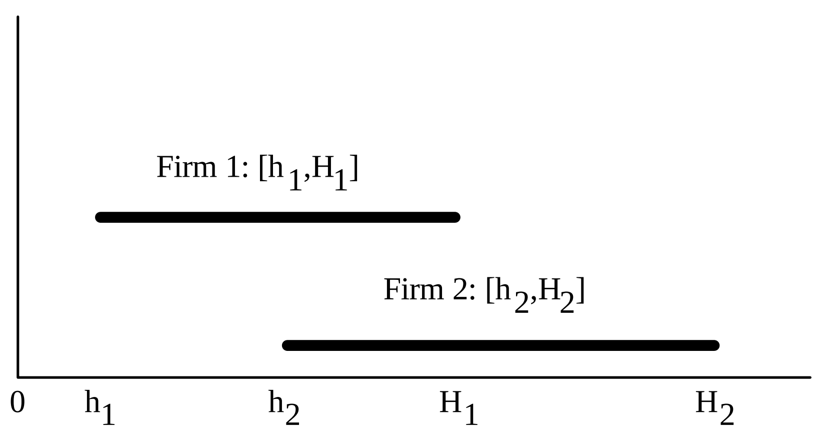


Figure 3 – Overlapping Network Intervals

The overlaps create *segments*, which are smaller than the intervals chosen by the firms in stage 2. Each segment is a unique area in which a certain competitive regime obtains. For example, households located in the segment $[h_2,H_1]$ in Figure 3 may buy from a fiber duopoly; households in other segments are served by monopolies or not at all. All firms know where the segments are located, and they can treat each segment differently in terms of capacity choices and price. A generic segment will be labeled [*a,b*] according to its endpoints, although it will be shown that the location of segments is not important.

In the second stage, firms choose capacity (size of routers, switches, portion of fiber to "light", etc.) for each segment in their interval; this capacity choice determines the maximum percentage of households in the firm's market interval that can be served in the final stage. Firms may install different capacities in different segments. Let the firm's capacity choice in the interval [*a,b*] be denoted $z_i(a,b)$. Since this capacity is expressed as a fraction, the maximum number of households in this segment that can be served is $z_i(a,b)(b-a)$. The cost of this capacity is $s(z)$ per household; in general, this unit cost is assumed nondecreasing and convex in household density. At the end of the second stage, all capacity decisions become common knowledge.

In the third stage, firms choose price and offer service to consumers who choose whether or not to buy service based on these prices; consumption takes place and profits are realized. Firms can charge different prices $p_i(a,b)$ in different segments; this price includes unlimited broadband service.[20] Since consumers in each segment are characterized by the same demand function, there is no price discrimination within a segment. Let $\mathbf{p}(a,b)$ be the vector of prices charged by the different firms in segment [*a,b*]. The fraction of households that demand connections from firm *i* at this price is denoted $q_i(\mathbf{p}(a,b))$.[21] At this stage we employ the usual Bertrand assumption that households purchase service from the lowest-priced firm, and split demand evenly between two or more firms which charge the same price. However,the capacity choice of the second stage limits the number of households that can be served, so $q_i(\mathbf{p}(a,b))(b-a) \leq z_i(a,b)(b-a)$. The cost to connect and serve a household is *c* which includes billing and any Internet charges levied on a per use basis. Again, price decisions become common knowledge.

It is important to note that the amount of demand and the costs of both capacity and hookups are not dependent on activity in adjoining segments. Such dependencies might occur if there were neighborhood demand externalities or cost-side economies of scope. Neighborhood effects are unlikely to occur in broadband networks because the primary use of the network is to access content over long distances rather than communicate with neighbors. Economies of scope are certainly possible in the backbone networks that connect different regions, but they are unlikely to be important in the local access environment where technology is deployed on a street-by-street basis.

Costs and Revenues Let *S* be a set of endpoints of all the segments created by the choices of intervals, with [*a,b*] a generic element of *S*. Recalling that $z_i(a,b) = 0$ for all $[a,b] \not\subset [h_i, H_i]$, the total costs for fiber firm *i* are

$$C_i = A + F(H_i) - F(h_i) + \sum_{[a,b]\in S} s(z_i(a,b)) \cdot z_i(a,b)(b-a) + \sum_{[a,b]\in S} c \cdot q_i(\mathbf{p}(a,b)) \cdot (b-a)$$

Revenues are the prices charged in each segment times the number of households that hook up in each segment; note that we assume a uniform price in each segment, with no price discrimination:

$$R_i = \sum_{[a,b]\in S} p_i(a,b) q_i(\mathbf{p}(a,b))(b-a)$$

Equilibrium We solve for a subgame perfect Nash equilibrium of the model presented above. The equilibrium will be calculated in three steps. First, the last two stages of the game are shown to be equivalent to Cournot competition. Second, the strategies in each segment are shown to be dependent only on the number of firms in the segment, not on the location of the segment. Third, it is shown that different areas of the city can (and in equilibrium must) support different numbers of firms.

Cournot Competition In the second and third stages of the game, the firms actually play separate games in each segment. First they simultaneously choose capacities, and then they simultaneously choose prices. Kreps and Scheinkman (1983) studied games of this type with homogeneous goods and identical costs. They show that the unique subgame perfect Nash equilibrium is equivalent to Cournot equilibrium. That is, firms choose capacities equal to the Cournot quantities and prices equal to the Cournot prices.

Friedman (1988) extended the analysis to games with heterogeneous goods and general cost functions. He shows that the Kreps-Scheinkman result holds over all ranges of prices for which profit functions are quasiconcave.

Proposition 1: The subgame perfect Nash equilibrium of stages two and three is equivalent to the Cournot equilibrium with appropriate inverse demand functions and costs $C(z)=s(z)+c$.

Proof: Straightforward application of the Friedman (1988) results.■

Proposition 2: The subgame equilibrium quantity percentages for segment $[a,b]$ depend only on the number of firms, not on the location of the segment.

Proof: See Appendix A.

The intuition behind this result is that (i) all fiber network costs are sunk by this stage of the game, so these costs do not enter into pricing decisions; (ii) consumers at all locations have identical demand characteristics and there are no locational interdependencies; and (iii) all firms face the same costs (capacity and marginal) and demands. Therefore, the only property that differs across segments is the number of firms.

Subgame Equilibrium for Entry and Location Decisions In the first stage, firms decide sequentially whether or not to enter, and if they enter in which interval in the linear city they will construct their network. This determines how many firms are in each segment. Firms expect Cournot prices and quantities in each segment as shown above. In equilibrium,

- Each firm will choose the interval that maximizes its profits, given the actions of firms that have previously entered and the anticipated actions of firms yet to enter.

- Entry occurs as long as there exists an interval for which operating profits are larger than network investment costs, given existing and anticipated competition.

In the following, we denote a generic segment as $[a,b]$, the number of firms operating in that segment as n, and the profits from that segment of a generic firm by $\Pi(n,a,b)$. Revenues are linear in *b* while costs (particularly network costs) are convex in *b*, so that profits are concave in *b*: $\frac{\partial^2 \Pi}{\partial b^2} < 0$.

Definition: For given *n*, let *L*(*n*) be the point at which the marginal cost of extending the fiber network is equal to the marginal revenue obtained from the extension. This is the geographic limit at which the marginal profitability of expanding the fiber area coverage into the less high-density area is zero. Then *L*(*n*) solves

$$L(n) = \begin{cases} \arg\max_b \Pi(n,a,b), \text{ for } \forall a,b \text{ such that } 0 \le a \le b, n > 0 \\ 0, \text{ for } n = 0 \end{cases}$$

From the concavity of profits in *b*, this maximum always exists. Note that *L*(*n*) may be zero for all *n* > 0, indicating that zero firms is the equilibrium. We state without proof the following results:

(a) $\frac{\partial \Pi(n,a,b)}{\partial b} \gtrless 0$ as $b \lessgtr L(n)$; this implies that *L*(*n*) is unique.

(b) $\frac{\P\Pi}{\P n} < 0$; firm profits are decreasing in the number of firms.

(c) $\frac{\P\Pi(n,a,L(n))}{\P a} < 0$; it is always profitable to expand toward the high-density area of the city (since higher household density implies lower fiber cost per household passed).

(d) $\arg\max_a \Pi(n,a,L(n)) = 0, \forall n > 0$; a network starting at the city center is more profitable than a network starting away from the center (follows from (c));

(e) $\frac{\P L(n)}{\P n} < 0$; the point at which marginal profitability is zero becomes closer to the city center as the number of firms increases. This follows from the convexity of *F*.

Denote Π(*n*) = Π(*n*,0,*L*(*n*)) and recall that firms are indexed by the order in which they enter and build their network.

Proposition 3: If *L*(1) > 0, then in equilibrium, the number of firms in the market *N* > 0 satisfies Π(*N*) ≥ 0 > Π(*N*+1). For *n* = 1,…,*N*, firm *n*'s network covers the interval [0,*L*(*n*)]. This equilibrium is unique.

Proof: see Appendix A.

Corollary: For *n* = 1,…,*N-1*, there are exactly *n* fiber firms operating in the segment [*L*(*n*+1),*L*(*n*)], and all *N* firms operate in the segment [0,*L*(*N*)].

Note that although all firms are identical, the equilibrium is not symmetric.[22] The densest "ring" around the city center supports the most firms, the next densest "ring" supports one less firm, and so forth, until $L(1)$, after which no firm builds a network and no service is offered.[23] By way of illustration, Figure 4 shows a possible equilibrium set of location decisions with three firms. This asymmetric equilibrium is in sharp contrast to the traditional Hotelling (1929) linear city model in both its original and updated (d'Aspremont, Gabszewicz, and Thisse, 1975) form. In the Hotelling model, firms choose a single location in the city and consumers travel to the firms. The equilibrium is symmetric in the number of customers of each firm. In the present model, consumers are immobile at their location in the city, and the broadband firms must build out to them. It is this difference, which is characteristic of infrastructure industries, that accounts for the asymmetric rather than symmetric equilibrium.

Not only is the geographic scope of each firm different from its competitors, the profits of each firm are different. For example, firm 1 realizes the same profits from the segment $[0,L(N)]$ as does firm N, and also realizes profits from the segment $[L(N),L(1)]$, which are not available to firm N. Thus, denoting by π_n the profits of firm n in equilibrium, we have that $\pi_1 > \pi_2 > \ldots > \pi_N$. The static model presented thus far does not explain which firms become more profitable; it simply states that different firms are more profitable. However, the equilibrium certainly suggests that firms may somehow vie to become "firm 1" in this model, a topic we return to in the dynamic model of strategic network investment in Section 5.[24]

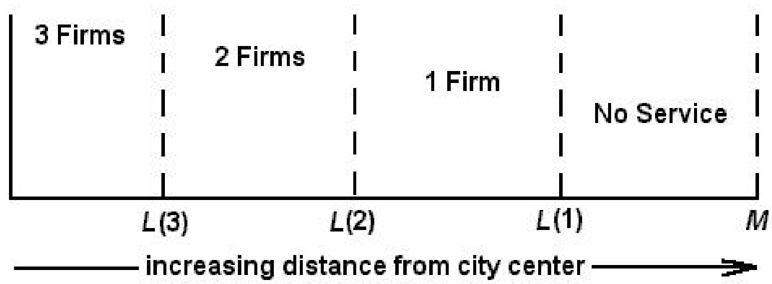


Figure 4 – Example of a Three-Firm Equilibrium

An Aside: Network Location Decision with a Universal Service Constraint If there is a universal service franchise requirement on entering firms to pass some fraction φ of households in the region, then their location decisions may be constrained. Denote by $\Pi_\varphi(n,L)$ the total profits of each of n firms which all build their networks to L, and L_φ the limit the firm will choose when there is a franchise requirement to serve the fraction φ of the city's households. Then

$$L_\varphi(n) = \begin{cases} L(n) & \text{if } L(n) \geq \varphi \cdot M \\ \varphi \cdot M & \text{if } L(n) < \varphi \cdot M \text{ and } \Pi_\varphi(n, \varphi \cdot M) \geq 0 \\ 0 & \text{if } L(n) < \varphi \cdot M \text{ and } \Pi_\varphi(n, \varphi \cdot M) < 0 \end{cases}$$

The number of firms N that enter with a universal service franchise requirement satisfies $L_\varphi(N) > 0 = L_\varphi(N+1)$.

4. Parameterization and Sensitivity Analysis

The questions that this paper seeks to answer require not only a theoretical model of competitive interactions, but empirical estimation of demand and cost functions. Since such systems have not yet been commercially deployed, we are unable to use standard econometric methods to estimate these cost and demand functions. Our empirical analysis must therefore be prospective in nature, relying on engineering estimates of costs and the existing, rather minimal survey information regarding demand. The technology of interactive broadband is well understood, so the engineering cost estimates are reasonable approximations. Marketing estimates of demand are subject to much more uncertainty.

In this section we parameterize the model of Section 3 using engineering cost data and marketing data. We then solve the game for (i) number of firms; (ii) equilibrium location decisions of the firms; and (iii) capacities, quantities, and prices of the firms in each market area. Since the demand estimates are the most uncertain, we vary the demand level by a factor of two in order to assess the range of possible outcomes. We examine three scenarios, varying the demand level in each one: a Base Case (best available estimates, free competition), a Pessimistic Cost Case (cost parameters 50% higher than the Base Case), and the imposition of a franchise requirement to provide fiber past 95% of the region's households (Base Case plus the universal service constraint).

The Market Setting The simulated market area discussed here is a medium-sized city whose metropolitan area contains 3 million households. This area includes a densely populated core, suburban areas, and a rural hinterland. Again, household demand functions are independent of location.

The calibration of the model from existing data sources is contained in Appendix B, including the assumptions regarding demand and cost functions for HFC, as well as the population density assumptions. The salient features of this calibration:

(i) prices are flat fee per month for unlimited usage (the same as today's most prevalent pricing structure);

(ii) the demand functions are linear.

(iii) the base demand ("today's" demand) level assumes 15% of households take broadband at a price of $50/month. At the end of 1998, approximately 30% of US households were online,[25] typically for Internet service at $20/month, so this would appear a realistic baseline.[26] At these prices, demand elasticity for broadband is about -2.23 (estimated by Mohan (1994)), although there is disagreement concerning this (see Federal Communications Commission, 1999, fn.260).

Demand Scenarios Since demand is quite uncertain, our principal variable that we examine is the demand level. In each scenario described below, we vary this level from the base demand (see above) to a demand level approximately that of today's cable TV systems (66% of households take service at $50/month). This level shifts the demand intercept to 2.3 times the base level demand intercept. In the graphs below we express the demand level as a percentage of base demand, ranging from 100% to 230%. The following are the scenarios we consider:

- Two city densities: a high-density city in which 75% of the households live in regions with 400 households per square mile, and a low-density city in which 50% of households live in such regions.

- Two policy scenarios: the open competition regime and the universal service regime.

- Two cost scenarios: the Base Case and the Pessimistic Cost Case (costs increased to 150% of the Base Case).

In Appendix C, the results of all scenarios are presented in graphs. For each scenario, the following equilibrium quantities are plotted as a function of the demand level:

(i) Number of households passed, for each firm; both the high-density and the low-density city.

(ii) Quantity demanded ("take rate") in each market area (valid for both density cities as a result of Proposition 2).

(iii) Price in the innermost area, in each market area (valid for both density cities as a result of Proposition 2).

(iv) Number of households passed, for each firm, in the open competition regime and the universal service regime, low-density city.

Each of these scenarios is shown for the Base Case, the Pessimistic Cost Case (costs 150% of base), for a total of twelve charts.

Results of the Analysis

The results of the scenario analysis are

Network scope issues:

> In both high- and low-density cities, entry occurs at demand levels about 20% higher than today's demand level. A second competitive supplier enters at a demand level about 75% higher than today, and a third enters at a demand level a bit more than double today's demand. In low density cities, customers with a low-density attribute do not have access to competitive service even after entry occurs.
>
> In high-density cities, firms extend their networks to the city edge at demand levels about 20-25% greater than levels at which entry occurs. Therefore, universal service (for geographic reasons) does not appear to be an issue in high-density cities.

Take rates (quantity) and price issues:

> Both take rates and prices are greater at greater demand levels, *ceteris paribus*. An increase in competition has the obvious effect on both variables.

Cost Assumptions issues:

For pessimistic costs, the profile of market-structure growth looks the same, but less entry and more delayed (two firms enter at 200% of today's demand rather than 175%). Prices are higher and costs are lower; however at cable-like demand levels, competition occurs.

Universal Service Franchise issues:

Our original hypothesis was that the imposition of a franchise requirement that all firms serve 95% of households in the metro region would impose such a high cost of entry that only a monopoly firm could survive. Such is not the case; the universal service franchise requirement leads to entry only at higher demand levels relative to the Base Case. At 150% of today's demand one firm enters (rather than 120% as in the Base Case). At 200% of today's demand, two firms enter (rather than 170% as in the Base Case). However, this result is sensitive to the cost assumptions: when the pessimistic costs are applied to the universal service case, there is no entry by a second firm even at high demand levels.

5. Strategic Investment Model

The static model predicts an asymmetric equilibrium in which firms differ in the profit they earn, depending on the geographic extent of their network. The static game has no strategic scope by which firms can vie to be the most profitable; it merely predicts that there will be profit differences. This suggests that the game structure could be enriched to include competition to be the largest firm; it is to this task we now turn.

We explicitly model the demand function as growing over time, eventually reaching a saturation level. We assume two firms; in each period, each firm chooses the size of its network. In the first period, one firm is assumed to be the first mover, in that it gets to choose its network size first. The second mover observes the chosen network size of the first mover before it decides on its network size. In subsequent periods, we assume that the larger firm gets to move first, with the option of expanding its network to accommodate the increased demand. The game continues until demand saturation is reached and no more network expansion occurs.

The first mover has an advantage because we assume that network investment is completely sunk for the entire game; thus, network investment has *interperiod commitment value* in this game. In contrast, capacity is sunk only for a single period, and thus does not have interperiod commitment value.

If demand were to reach its saturation level in a single period, never to increase again, the outcome of this essentially static game is obvious: the first mover builds its network to $L(1)$ and the second mover then builds to $L(2)$, the duopoly market limit.

If demand is growing over time, however, a new strategic alternative becomes available. If the first mover were only to build to the $L(1)$ level for period 1 demand, it could pay the second mover to build beyond this level, in order to capture the right to be first mover in subsequent periods. Eventually, the first mover in the period in which demand saturation occurs becomes the larger, more profitable firm, and that prize may be worth some overinvestment in earlier periods in order that the firm can capture the available rents. Of course, if it would pay the second mover to build past $L(1)$ in the first period, it would also pay the first mover to build beyond $L(1)$ if by doing so it can prevent the second mover from becoming the larger firm, and thus gain first mover advantage in subsequent periods.

The Dynamic Game The dynamic game is a state-space game, in the sense of Fudenberg and Tirole (1986), in which the state in each period is the demand level and the previous network size. We derive the closed loop equilibrium conditions for this game.

The structure of the game is a simple repeated play extension of the previous game, but with only two players. Demand increases exogenously in periods $t = 1,\ldots,T$. One firm is the first mover in the network investment game (stage 1 of the static model) in the first period. We assume that network investment is sunk, so that constitutes a commitment. After the network for period 1 is built, stages 2-3 of the previous model occur. The capacity choice of stage 2 is sunk only until the end of the period, so it has no inter-period commitment value. At the end of each period, the game is repeated (stages 1-3). The firm with the larger existing network moves first in each period. Since network investment is sunk, existing networks can only be expanded, not shrunk. However, capacity can be either expanded or shrunk from the existing level. Demand stops growing in period T; in subsequent periods, the demand function is identical to that which occurs in period T.

In the dynamic game, we assume that the network cost $F(\cdot)$ is a capital charge on total network investment, not the investment itself. For example, if a firm builds a network in the interval $[0,x]$ in period t, it pays $F(x)$ in each period t, $t+1,\ldots$ [27]

In each period, there are (at most) two firms in the market. Using the results of the static game, the equilibrium will be asymmetric, with both firms sharing a duopoly market starting from the city center, and one firm enjoying a monopoly market beyond the duopoly region. Let

$P_t(n,a,b)$ = profit in segment $[a,b]$ to one of n firms operating in that segment in period t

As before, we denote the static monopoly and static duopoly regions as $L_t(1)$ and $L_t(2)$, respectively. Let b be the discount factor.

The Final Period T At the start of the final period, the larger of the two firms has a network size of s_{T-1} and the smaller has a network size of j_{T-1} (where s, j refer to "senior" and "junior"). At no time period is there a profitable opportunity to build past $L_T(1)$ because by definition even a monopoly in the final, highest-demand period does not generate enough operating profit to justify building beyond that size. Therefore even with dynamic strategies it will always be the case that $s_{T-1} \leq L_T(1),\ j_{T-1} \leq L_T(1)$. Since both firms may profitably build to the static duopoly level $L_T(2)$ in the final period, then in equilibrium each will have built its network at least to this level. Therefore, the only area of strategic significance is that beyond $L_T(2)$, so we ignore any profit from operating up to $L_T(2)$ by normalizing it to zero. Denote $S_{T-1} = \max\{s_{T-1}, L_T(2)\}$ and $J_{T-1} = \max\{j_{T-1}, L_T(2)\}$; we know that these are the minimum size networks of the two players in period T.

Optimal Actions and Payoffs in the Final Period The larger firm is first mover, and can thus capture the large-firm rents into the future if it expands to the monopoly level. Since this is more profitable than settling for duopoly rents into the future, this is its optimal action:

$$S_T^* = L_T(1)$$

and the payoff (over and above operating within $L_T(2)$) for this action is

$$V_T^{S*}(J_{T-1}) = \frac{\Pi_T(2, L_T(2), J_{T-1}) + \Pi_T(1, J_{T-1}, L_T(1))}{1-\beta}$$

The optimal action for the second mover is $J_T^* = J_{T-1}$ and the payoff for this action is

$$V_T^{J*}(J_{T-1}) = \frac{\Pi_T(2, L_T(2), J_{T-1})}{1-\beta}$$

From the definition of $L_T(2)$, this payoff is zero if $J_{T-1} = L_T(2)$ and negative otherwise.

The Next to Final Period Consider the small firm at the beginning of period T-1 with an existing network of size J_{T-2}, after the large firm has already chosen its network size S_{T-1}. The small firm may choose to stay small, thus ensuring it will be the second mover again in period T. If it so chooses, the best it can do is maintain its present position, $J_{T-1} = J_{T-2}$, in which case its current return is zero and its return in the next period is $\beta \cdot V_T^{J*}(J_{T-2})$. Alternatively, the small firm may choose to "leapfrog" the large firm in order to gain the benefits of first mover in the final period. The most profitable leapfrog strategy is $\Lambda_{T-1}(S_{T-1}) = \max\{L_{T-1}(1), S_{T-1} + \varepsilon\}$; that is, expand to the static monopoly level if that is greater than the large firm's move; otherwise expand just beyond the large firm's network. The leapfrog strategy has value

$$\Pi_{T-1}(2, J_{T-2}, S_{T-1}) + \Pi_{T-1}(1, S_{T-1}, \Lambda_{T-1}(S_{T-1})) + \beta V_T^{S*}(S_{T-1})$$

Proposition 4: For all $J_{T-2} \geq 0$, the leapfrog value is decreasing in S_{T-1}.

Proof: See Appendix A.

Proposition 5: For all $J_{T-2} > 0$, there exists an $\tilde{S}_{T-1}$ such that the leapfrog value to the small firm equals the "stay small" value.

Proof: see Appendix A.

If the first mover builds a network of size $\tilde{S}_{T-1}$ or greater, then the second mover is dissuaded from leapfrogging; the first mover thus *preempts* the second mover, maintaining its first mover advantage into the next period. The Proposition shows that preemption by the first mover is possible.

Optimal Actions and Payoffs The first mover in period T-1 observes the small firm's network size J_{T-2} and forecasts the optimal response of the second mover to his action S_{T-1}. If the first mover chooses $S_{T-1} \geq \tilde{S}_{T-1}(J_{T-2})$, the second mover remains small and the first mover is also the first mover in the final period. If the first mover chooses preemption, the best move is $\bar{S}_{T-1} = \max\{S_{T-2}, L_{T-1}(1), \tilde{S}_{T-1}(J_{T-2})\}$; that is, the firm chooses the preemption level, unless (a) the static monopoly level preempts, or (b) the firm's current network size is larger than either level. The incremental value of this strategy, including the value of being first mover in the final period and correctly anticipating the second mover's action, is

$\Pi_{T-1}(1, S_{T-2}, \bar{S}_{T-1}) + \beta V_T^{S*}(J_{T-2})$.

If the first mover chooses not to preempt, then the firm correctly anticipates that the second mover will leapfrog, so its best strategy is to stay small, choosing a network of size S_{T-2}. The incremental payoff to this strategy would be 0 in period $T-1$ and $\beta V_T^{J*}(S_{T-2})$ from period T.

Proposition 6: If the first mover chooses to enter, then it always preempts.

Proof: see Appendix A.

The intuition is that it is always more profitable for the large firm to preempt than it is for the small firm to leapfrog, since a larger network is required to preempt a larger firm: $\tilde{S}_{T-1}(S_{T-2}) \geq \tilde{S}_{T-1}(J_{T-2})$. Therefore, the optimal action for the first mover is to preempt: $S^*_{T-1} = \max\{S_{T-2}, L_{T-1}(1), \tilde{S}_{T-1}\}$ This preemption result is robust to any parameterization of the model so long as (i) the discount rate is less than 1, and (ii) the costs to building a larger network are continuous.

The payoff of the preemption strategy at T-1 for the first mover is

$$V^{S*}_{T-1}(J_{T-2}) = \Pi_{T-1}(2, L_{T-1}(2), J_{T-2}) + \Pi_{T-1}(1, J_{T-2}, \bar{S}_{T-1}(J_{T-2})) + \beta V_T^{S*}(J_{T-2})$$

The optimal action for the second mover is $J^*_{T-1} = J_{T-2}$, with payoff

$$V^{J*}_{T-1}(J_{T-2}) = \Pi_{T-1}(2, L_{T-1}(2), J_{T-2}) + \beta V_T^{J*}(J_{T-2}).$$

Periods 1,…,T-2 The period game in these periods is identical to that of period T-1, with a change of subscripts. In each period, the optimal strategy for the first mover is to preempt; the second mover (assuming this firm starts with a small network) chooses the static duopoly level. In the early periods of the game, the future value of being first mover is quite large, as it includes not only the profits at the end of the game, but profits in the intermediate periods as well.

Discussion of Equilibrium It is important to repeat that only network size is a permanently sunk investment and therefore has interperiod commitment value. Within each period, the capacity and pricing decisions can and will be modified to reflect demand and competitive conditions, but network size can never be reduced. This difference in commitment value causes the main result of the dynamic model: relative to the static case, preemption affects the network size of the first mover, but it does not affect take rates and prices. A direct implication of this result is that a second-mover, operating as a duopoly competitor, receives the same profits and has the same incentives to enter the market as in the static case. Thus, preemption does not reduce competition relative to the static model. Both the first and second mover offer the same service in the same locations and at the same prices in both the static and dynamic cases. But in the dynamic case, the first-mover also offers service in some additional locations in order to capture the rents which accrue to the larger firm.

The preemption result of this model is quite different from many dynamic competition models in which preemption is anticompetitive. For example, Tirole (1988, pg. 315) points out that many capacity-investment games resemble the traditional Stackelberg equilibrium: entry cannot be blockaded, but it can be accommodated in such a way as to reduce the entrant's profit opportunities. Spence (1979) and Fudenberg and Tirole (1983) present dynamic models in which a first-mover can reduce the strength of entry. In these models, geography is not an issue, and firms can make credible commitments to capacity. In contrast, broadband network providers can make credible commitments to network size but not to capacity. It is this difference which accounts for the result presented here.

Because the model of dyanmic preemption is a "race" to obtain the monopoly area, its closest parallels in the industrial organization literature are models of patent races. Fudenberg et. al. (1983) and Harris and Vickers (1985) present models of patent races in which there is the possibility of leapfrogging. Both papers find that the first-mover firm can preserve its advantage throughout the game by staying just far enough ahead to prevent the second-mover from leapfrogging.

In this model, the preemption strategy can be thought of as rent dissipation; in order to capture the rents that accrue to the larger firm, the first mover is willing to overinvest along the demand growth path. Posner (1975) discusses rent dissipation, proposing that (i) rents will be dissipated by firms' efforts to obtain them, and (ii) these expenditures are socially wasteful. Fudenberg and Tirole (1987) cite several industrial organization models relevant to Posner's propositions.

The results of this model tend to confirm Posner's first proposition: the rents from the monopoly area are partially dissipated through the costs of preemptive investment. If the starting time period were pushed back sufficiently long before demand began to grow, then there would be complete rent dissipation. However, the preemptive overbuilding is not purely socially wasteful. While a socially optimal network would achieve a higher take rate than the preemptive network, we show below that the number of homes passed by the preemptive network is closer to the social optimum than the network of a myopic firm.

Sensitivity Analysis The dynamic game was simulated using the engineering model with identical cost and demand assumptions as for the static model. We assume three demand growth scenarios, in which demand increases linearly from "today's" level to "cable-like" levels in T = 5, 10, and 20 years, after which it is constant. The socially optimal network size is also computed, in which usage, capacity, and network size are determined to maximize total social surplus.

In Appendix C, the results are presented in graphs; for simplicity, we consider only the low-density city.[28] For the Base Case, Pessimistic Cost Case, and the Universal Service Franchise Case, the following equilibrium quantities are plotted as a function of demand level:[29]

- Number of households passed in dynamic equilibrium, for both firms, for T = 5, 10, and 20 years.
- Number of households passed in the equivalent static equilibrium, for both firms (same as in Appendix C).
- Number of households passed in the socially optimal network expansion path.

Since prices and take rates in dynamic equilibrium are identical to the corresponding static model, these are not repeated.

Results of the Analysis In all cases, the preemption network of the first mover is larger than the static monopoly network ($\tilde{S}_t > L_t(1)$) for low demand levels. At demand levels near saturation, the static monopoly level is preemptive ($\tilde{S}_t < L_t(1)$). Further, the faster is growth the larger is the preemptive network; $\tilde{S}_t^{(T=5)} > \tilde{S}_t^{(T=10)} > \tilde{S}_t^{(T=20)}$. This appears to reflect the fact that the "prize" (being the large firm forever) is closer to the present with fast growth, and therefore of greater value.[30]

In the Universal Service Franchise Case, these incentives are reflected in earlier entry by the single firm. In this case, leapfrogging and preemption take the form of early entry rather than larger networks, and strategic dynamic behavior results in earlier deployment relative to the static model (and the socially optimal network).

Perhaps most interesting is the result that for the examples presented,[31] the equilibrium preemptive network is larger than the socially optimum network in the earlier years. It is no surprise that this network is always larger than the monopoly network. What is a surprise is that in most cases the large-firm optimal expansion path with preemption is larger than the socially optimal network. The lure of large-firm profits encourages networks even larger than a social planner would build.[32]

6. Conclusions

The object of this paper is to draw conclusions concerning the future market structure of broadband infrastructure in the absence of price and entry regulation. The research draws heavily on a particular model of competitive behavior and a particular calibration of that model using engineering data and preliminary demand estimates, as well as many other assumptions. As this analysis precedes significant deployment of these systems, this more conjectural mode of analysis is forced upon us. Clearly, the results are only as compelling as the model, the estimates, and the assumptions; while these appear reasonable to the authors, the absence of information that economists find compelling requires that these results be viewed as highly tentative. With that strong caveat, we draw the following conclusions:

Competition in the provision of interactive broadband infrastructure to metropolitan area households is likely if the market is left unfettered. While this infrastructure market is clearly not perfectly competitive, it would appear that two or even three firms can offer fiber infrastructure at higher demand levels and survive. Strategic dynamic behavior takes the form of dissipating rents by increasing network size relative to the static model, which is an unambiguous gain for consumers.

If costs are greater than anticipated, entry of firms into the market is delayed, and competition is lessened. However, the model suggests that more than one firm can be supported at higher demand levels.

Universal Service In high-density cities, firms quickly expand to reach the limits of the metropolitan area, so all households have access to the service. In low-density cities, this expansion is more gradual, and households close to the city's edge can expect few competitive options. However, geographic coverage at high demand levels is 86%, even in the low-density city Pessimistic Cost case, indicating that the market can achieve near-universal service.

Requiring that all entrants pass 95% of households adds substantially to network costs, making entry more expensive. This delays entry, and delays competition, but it does not eliminate it.

Strategic Network Preemption is likely to occur, and works in the favor of consumers, in that firms vying to be the largest are willing to dissipate rents via increased network size. In equilibrium, prices, take rates, and competition are identical to the static model results.

Timing of Competitive Entry An obvious feature of all market scenarios is that in the early periods of demand growth, the market consists of a single firm. Entry does not occur until substantial demand growth has occurred after the initial entry. During this period, it is likely to appear that the market is characterized by natural monopoly, and that some form of government intervention is needed. Indeed, if demand growth caps at, say, 140% of today's demand level, then this may well be the case. If, however, demand continues to grow, eventually approaching or exceeding that realized by cable TV today, then the market is likely to evolve to a more competitive outcome, provided government intervention at an earlier stage does not preclude the market from functioning. This suggests that some patience may be required before concluding that broadband infrastructure is a natural monopoly.

Suggestions for future research The assumptions we make in this paper naturally suggest areas of future research in the area of market structure of broadband:

> **The form of competition** The model here assumes all players are rational and know that the other players will play rationally. However, competitors may believe that one firm will behave irrationally (with some probability) and provide excess capacity and very low prices in an attempt to drive others out of the market, as in Milgrom and Roberts (1982) and Kreps and Wilson (1982). The importance of irreversible infrastructer investment would seem to make this less likely. However, the interaction between reputation effects and high sunk costs could be a fertile area of research.
>
> **Interaction with related markets** The model here assumes that the market for broadband infrastructure functions independently of related markets, such as the content market and the PC market, assuming both Internet content and PCs are already ubiquitous and broadband would "piggyback" on these markets. However, recent business actions by AT&T and America Online suggests that bundling broadband infrastructure with Internet "portal" services (that is, the first screen that customers see when they access the Internet) may be an important business strategy. Additionally, customers' choice of broadband services may be influenced by preferential treatment via the PC operating system/desktop. Further research is required in order to determine whether or not such market strategies are effective in the long run. If they are, then regulatory attempts to open access to broadband facilities (and the desktop) may be appropriate.
>
> **Collusion** The model here assumes that firms do not collude, nor are there mergers. Research focused on incentives for mergers, joint ventures, and/or collusion in network industries could be fruitful in determining if competition is indeed feasible in the long run in these markets.

Switching Costs The model here assumes that customers can switch costlessly between competitors where available. If switching costs were large, then the benefits of competition would be correspondingly less. Empirical research on switching costs for telecommunications services generally and broadband in particular could shed light on this issue.

Incumbency The model here assumes *de novo* entry into broadband; in fact, cable television and telephone companies are likely to be early entrants, with a purported advantage of an existing network, complementary products, and existing customer base. In this sense, the research is conservative; if *de novo* entry is feasible, how much more so if there is an advantage of incumbency. It is not clear, however, that incumbency in a related but regulated industry, especially if customer relations and competitive nimbleness are not particularly good, is an advantage. Empirical research on the benefits and costs of incumbency could clarify if deployment might occur even more rapidly than our model suggests.

Demand differences The model here focuses on cost differences across households and neighborhoods as the driver of equilibrium location decisions by infrastructure providers. Clearly, demand differences will exist and both demand and cost will in practice drive location decisions. Little is known about demand patterns as of this writing; as market research improves, knowledge of demand differences could significantly affect the results of this research, as discussed in the text.

Appendix A

Proof of Proposition 2: Let $n = 1,\ldots,N$ firms be offering service in segment $[a,b]$, with demands q_n and total demand $Q^{a,b} = \sum q_n$ and inverse demand in $[a,b]$ given by $P(Q^{a,b})$. The costs incurred in the first two stages are sunk at this point in the game, so the payoff for each firm in segment $[a,b]$ is

$$\pi_n = \left[P\left(Q^{a,b}\right) - c(q_n)\right]q_n(b-a).$$

The first order condition for firm n is

$$\frac{\partial \pi_n}{\partial q_n} = \left[P\left(Q^{a,b}\right) - C(q_n)\right](b-a) + \left[P'\left(Q^{a,b}\right) - C'(q_n)\right]q_n(b-a) = 0, \text{ or}$$

$$\left[P\left(Q^{a,b}\right) - C(q_n)\right] + \left[P'\left(Q^{a,b}\right) - C'(q_n)\right]q_n = 0$$

The (common) solution to the last FOC depends only upon the number of firms and not on the segment $[a,b]$. ■

Proof of Proposition 3: Since the firms move sequentially, there are no mixed strategies in this game. To see that this is a Nash equilibrium, consider firm n, whose network covers the interval $[0,L(n)]$. Suppose firm n increases its left interval boundary from 0 to a, $L(j) < a < L(j\text{-}1)$, $j > n$. The change in profit from this deviation is

$$\sum_{k=N+1}^{j+1}\left(-\Pi(k, L(k), L(k-1)\right) - \Pi(j, L(j), a)\,.$$

From the definition of $L(n)$ and the concavity of Π, each summand is negative, so any deviation that reduces the firm's right interval boundary results in lower profits for the firm.

Suppose now that firm n decreases its right interval boundary from $L(n)$ to b, $L(j) < b < L(j\text{-}1)$, $j > n$. The change in profit from this deviation is

$$\sum_{k=n}^{j-1}\Pi(k,0,L(k)) - \Pi(k,0,L(k+1)) + [\Pi(j,0,L(j)) - \Pi(j,0,b)].$$

From the definition of $L(n)$ and the concavity of Π, each summand is negative, so any deviation that reduces the firm's right interval boundary results in lower profits for the firm.

Suppose next that firm n increases its right interval boundary from $L(n)$ to b, $L(j) < b < L(j\text{-}1)$, $j < n$ (for $j = 1$, let $L(j\text{-}1) = \infty$). Then the profit from this deviation is

$$\sum_{k=n}^{j-1}\Pi(k,0,L(k)) - \Pi(k,0,L(k-1)) + [\Pi(j,0,L(j)) - \Pi(j,0,b)].$$

From the definition of $L(n)$ and the concavity of Π, each summand is negative, so any deviation that reduces the firm's right interval boundary results in lower profits for the firm.

Lastly, suppose firm n exits entirely; since each firm earns positive profits in the hypothesized equilibrium, this deviation results in lower profits for the firm. Therefore, since all possible deviations result in lower profits, the hypothesized equilibrium is Nash.

To show that this equilibrium is unique, consider any other market structure with K firms, with each firm j's network in the interval $[h_j,H_j]$, $j = 1,\dots,K$, ordered by increasing H_j. For simplicity, we consider only market structures for which $h_j \neq H_j$, for all i, j (the argument is more complex but essentially the same without this assumption). Suppose firm j reduces its left interval boundary from h_j to $h_j - \varepsilon$, which it can do provided $h_j > 0$. From (c) above, this deviation increases profits, so $h_j > 0$ cannot be an equilibrium. Hence, all equilibria must have $h_j = 0$, for all j.

Suppose that firm j changes its right interval from $H_j \neq L(j)$ by ε closer to $L(j)$ (that is, $H_j + \varepsilon$ for $H_j < L(j)$ or $H_j - \varepsilon$ for $H_j > L(j)$). From the definition of $L(j)$ and the concavity of Π with respect ot the right-hand interval boundary, this change reduces profits, so $H_j \neq L(j)$ cannot be a Nash equilibrium. Thus, all Nash equilibria are characterized by firms building networks in the intervals $[0, L(j)]$, $j = 1,\dots,K$. Further, if $K < N$, then entry into the interval $[0,L(K+1)]$ is profitable; likewise, if $K > N$, firm K is earning negative profits, so exit is profitable. In either case, K firms cannot be a Nash equilibrium. Therefore, the unique Nash equilibrium is as hypothesized.■

Proof of Proposition 4: Writing out the expression fully gives:

$$\Pi_{T-1}(2,J_{T-2},S_{T-1})+\Pi_{T-1}(1,S_{T-1},\Lambda_{T-1}(S_{T-1}))+\frac{\beta}{1-\beta}\Pi_T(2,L_T(2),S_{T-1})+\frac{\beta}{1-\beta}\Pi_T(1,S_{T-1},L_T(1)).$$

Recall from the discussion of the static model that $\frac{\partial\Pi(n,a,b)}{\partial b}<0$ for $b>L_t(n)$. Since $\Lambda_{T-1}(S_{T-1})$ is increasing in S_{T-1}, this condition applies to the second term. Also recall that $\Pi_t(1,a,b)>\Pi_t(2,a,b)$ for all a,b. This means that $\frac{\partial}{\partial b}\left(\Pi_t(2,a,b)+\Pi_t(1,b,c)\right)<0$. Combining these two facts indicates that the entire payoff must also be decreasing in S_{T-1}. ■

Proof of Proposition 5: The "stay small" value is $\beta V_T^{J*}(J_{T-2})=\beta\frac{\Pi_T(2,L_T(2),J_{T-2})}{1-\beta}$. This value is unaffected by changes in S_{T-1}. It has already been shown (Proposition 4) that the leapfrog value is decreasing in S_{T-1}. The lower bound on the leapfrog value is

$$\Pi_{T-1}(2,J_{T-2},M)+\Pi_{T-1}(1,M,M)+\frac{\beta}{1-\beta}\Pi_T(2,L_T(2),M)+\frac{\beta}{1-\beta}\Pi_T(1,M,L_T(1))$$

$$=\Pi_{T-1}(2,J_{T-2},M)+\frac{\beta}{1-\beta}\Pi_T(2,L_T(2),M)$$

Both terms must be negative since $\frac{\partial\Pi_t(n,a,b)}{\partial b}<0$ for $b>L_t(n)$. Then by comparison with the "stay-small" value, it can be shown that the lower bound on the leapfrog value is weakly less than the lower bound on the "stay-small" value for any J_{T-2}.

Since the leapfrog value decreases in S_{T-1} while the stay-small value is constant in S_{T-1}, and since the lower bound on the leapfrog value is less than or equal to the lower bound on the stay-small value for any J_{T-2}, there must be some size $\tilde{S}_{T-1}(J_{T-2})$ such that the two values are equal. ■

Proof of Proposition 6: The first mover preempts if the incremental value of preemption is greater than the incremental value of staying small, i.e. if

$$\Pi_{T-1}(1, S_{T-2}, \bar{S}_{T-1}) + \beta V_T^{S*}(J_{T-2}) \geq \beta V_T^{J*}(S_{T-2})$$

Preemption requires building to at least $\tilde{S}_{T-1}(J_{T-2})$. The definition of $\tilde{S}_{T-1}(J_{T-2})$ is that

$$\Pi_{T-1}(2, J_{T-2}, \tilde{S}_{T-1}(J_{T-2})) + \Pi_{T-1}(1, \tilde{S}_{T-1}(J_{T-2}), \Lambda_{T-1}(\tilde{S}_{T-1}(J_{T-2}))) + \beta V_T^{S*}(\tilde{S}_{T-1}(J_{T-2})) = \beta V_T^{J*}(J_{T-2})$$

In the following steps it will be shown that the RHS of the inequality is smaller than the RHS of the equality, and that the LHS of the inequality is larger than the LHS of the equality. That means that the definition of $\tilde{S}_{T-1}(J_{T-2})$ implies that the preemption inequality must hold.

First, recall that $\beta V_T^{J*}(\bullet) = \beta \dfrac{\Pi_T(2, L_T(2), \bullet)}{1-\beta}$ and that $\dfrac{\partial \Pi(n,a,b)}{\partial b} < 0$ for $b > L_t(n)$. Since $S_{T-2} \geq J_{T-2}$, then $\beta V_T^{J*}(S_{T-2}) \leq \beta V_T^{J*}(J_{T-2})$.

Second, recall that $\beta V_T^{S*}(\bullet) = \beta \dfrac{\Pi_T(2, L_T(2), \bullet) + \Pi_T(1, \bullet, L_T(1))}{1-\beta}$, and that $\dfrac{\partial \Pi(n,a,L(n))}{\partial a} < 0$. Since $\tilde{S}_{T-1}(J_{T-2}) \geq J_{T-2}$, then $\beta V_T^{S*}(J_{T-2}) \geq \beta V_T^{S*}(\tilde{S}_{T-1}(J_{T-2}))$.

It remains to show that

$$\Pi_{T-1}(1, S_{T-2}, \bar{S}_{T-1}) \geq \Pi_{T-1}(2, J_{T-2}, \tilde{S}_{T-1}(J_{T-2})) + \Pi_{T-1}(1, \tilde{S}_{T-1}(J_{T-2}), \Lambda_{T-1}(\tilde{S}_{T-1}(J_{T-2})))$$

First take the case where $\tilde{S}_{T-1}(J_{T-2}) \geq L_{T-1}(1)$. In that case, $\Pi_{T-1}(1, \tilde{S}_{T-1}(J_{T-2}), \Lambda_{T-1}(\tilde{S}_{T-1}(J_{T-2}))) \leq 0$. Now note that $\Pi_{T-1}(2, J_{T-2}, \tilde{S}_{T-1}(J_{T-2}))$ can be broken up into

$$\Pi_{T-1}(2, J_{T-2}, S_{T-2}) + \Pi_{T-1}(2, S_{T-2}, \tilde{S}_{T-1}(J_{T-2}))$$

of which the first term must also be negative. Then all that is required is that $\Pi_{T-1}(1, S_{T-2}, \bar{S}_{T-1}) \geq \Pi_{T-1}(2, S_{T-2}, \tilde{S}_{T-1}(J_{T-2}))$, which must be true because $\dfrac{\partial \Pi}{\partial n} < 0$.

Now take the case where $\tilde{S}_{T-1}(J_{T-2}) < L_{T-1}(1)$. Then $\bar{S}_{T-1} = L_{T-1}(1)$ and $\Lambda_{T-1}(\tilde{S}_{T-1}(J_{T-2})) \geq L_{T-1}(1)$. The relevant inequality is now

$$\Pi_{T-1}(1, S_{T-2}, L_{T-1}(1)) \geq \Pi_{T-1}(2, J_{T-2}, \tilde{S}_{T-1}(J_{T-2})) + \Pi_{T-1}(1, \tilde{S}_{T-1}(J_{T-2}), \Lambda_{T-1}(\tilde{S}_{T-1}(J_{T-2})))$$

Breaking up the first and second terms gives

$$\mathrm{P}_{T-1}(1,S_{T-2},\tilde{S}_{T-1}(J_{T-2}))+\mathrm{P}_{T-1}(1,\tilde{S}_{T-1}(J_{T-2}),L_{T-1}(1))$$
$$\ddagger\mathrm{P}_{T-1}(2,J_{T-2},S_{T-2})+\mathrm{P}_{T-1}(2,S_{T-2},\tilde{S}_{T-1}(J_{T-2}))+\mathrm{P}_{T-1}(1,\tilde{S}_{T-1}(J_{T-2}),\mathrm{L}_{T-1}(\tilde{S}_{T-1}(J_{T-2})))$$

Now by the logic used above, the first term on the LHS is greater than the second term on the RHS, and the first term on the RHS is negative. Then all that remains is to show that

$$\mathrm{P}_{T-1}(1,\tilde{S}_{T-1}(J_{T-2}),L_{T-1}(1))\ddagger\mathrm{P}_{T-1}(1,\tilde{S}_{T-1}(J_{T-2}),\mathrm{L}_{T-1}(\tilde{S}_{T-1}(J_{T-2})))$$

Now when $\tilde{S}_{T-1}(J_{T-2})<L_{T-1}(1)$, then $\mathrm{L}_{T-1}(\tilde{S}_{T-1}(J_{T-2})\geq L_{T-1}(1)$. This implies that either the expression holds with equality or that the RHS can be broken up into

$$\mathrm{P}_{T-1}(1,\tilde{S}_{T-1}(J_{T-2}),L_{T-1}(1))+\mathrm{P}_{T-1}(1,L_{T-1}(1),\mathrm{L}_{T-1}(\tilde{S}_{T-1}(J_{T-2}))),$$

in which case the second term is negative and so the inequality would hold strictly.

Putting all these inequalities together shows that the definition of $\tilde{S}_{T-1}(J_{T-2})$ implies that preemption is better than staying small for the first mover. ■

Appendix B

Calibration of the Model from Existing Data Sources

The density of the population at *m* households from the city center in our representative metropolitan area is assumed to follow an exponential form:

$$d\left(\frac{m}{\overline{M}}\right) = \mathrm{h} e^{-\mathrm{l}\frac{m}{\overline{M}}}.$$

where *m* is the number of households and $\overline{M}$ is the outer limit of the linear city. The population density at the city center (*m* = 0) is h; Jones and Shmania take 1,400 people per square mile as their highest population density, although higher densities are actually common in cities. We assume h=1,400. The parameter l indicates how quickly population density falls as one moves away from the center of the city. The larger is l the smaller the fraction of the population that lives in high-density areas. In order to make this more meaningful, we re-parameterize this function using the fraction q of households that live in regions with density greater than 400 people per square mile.[33] Setting $d(\mathrm{q})$=400 yields the required re-parameterization: $\mathrm{l} = \dfrac{\ln \mathrm{h} - \ln 400}{\mathrm{q}}$.

It appears that most US cities have q densities in the range of 0.40 to 0.80, corresponding to newer western cities at the low end (low-density cities) and older eastern and Midwestern cities at the high end (high-density cities).

Demand This analysis uses a linear demand curve: $P(Q)=\mathrm{a}-\mathrm{b}Q$. The quantity *Q* is a percentage of households, and price is expressed as a monthly charge for unlimited use. A simple estimate of the fiber demand curve is available in Mohan (1994) by extrapolating from two price/quantity points.[34] According to this estimate, a = 120 and b =217.42.

All demand functions in this simulation maintain the slope value at 217.42. We note that in 1998 there were almost 30 million ISP customers,[35] approximately 30% of US households. Generally these customers purchased service at a price of $20.00 per month and a bandwidth of 28-56 Kbps. In order to establish a "current" demand level, we assume that half of these online households would purchase broadband service at $50.00 per month: *Q*=0.15, *P*=$50. This corresponds to a=82.5. In order to establish a saturation level of demand, we note that currently about 2/3 of US households subscribe to cable TV, which we consider to be a mature electronic distribution product; we assume that broadband service could eventually reach this penetration level: *Q*=0.66, *P*=$50. This corresponds to a=194, or 235% of the assumed "current" demand level. In the analysis, we vary a in order to examine the sensitivity of the results to demand variation (in the static model), and demand growth (in the dynamic model).

Costs Cost estimates are needed for both the network costs of installing cables and associated hardware and for the capacity costs of installing routers to accommodate traffic and hookups for individual houses.

We use cost estimates from Omoigui (1995) for the costs of an advanced hybrid-fiber-coax network (HFC) network. A summary of these estimates is presented in Omoigui et. al. (1996).

The Omoigui analysis examines several different network architectures. The one which seems to best represent the general-purpose broadband networks discussed in this paper consists of 500 home nodes, 25% peak coincident usage, with 2.85Mbps available to each home during this peak usage.

Fixed Costs The network cost parameterization described below incorporates fixed costs of $q \times$ \$18.5 million into the network cost function.

Network Costs The source used for relating network cost to population density is Jones and Shmania (1995). They estimate the cost to build a broadband HFC network with capacity to serve 5% of the houses passed, where cost is a function of population density.

An additional source, Omoigui et. al. (1996), contains more technical details on advanced HFC networks and estimates the cost of installing a network that provides conventional cable television to 60% of homes passed and broadband services to 5% of homes passed.

According to Jones and Shmania, the cost per house passed begins rising dramatically at population densities of less than 400 per square mile, so the proportion of the population living at density levels higher than 400 per square mile is used as a parameter of the density function. Fitting the Jones and Shmania cost estimates with a power function yields an estimate of the cost per house passed as a function of density:

$$c(d) = 754 + 65.7 \times 10^{6} \cdot d^{-2.1}$$

The cost estimate in Omoigui et. al. for a broadband HFC network serving 5% of the homes passed is \$1,050 per home passed at a population density of 1,591 people per square mile.[36] Of this figure, \$168 is attributable to the set-tops provided to the analog cable customers,[37] so a figure of \$882 per home passed is more comparable with Jones and Shmania's estimates. This figure is about 15% higher than the estimate of \$766 per home passed obtained from evaluating *c*(1,591).

Using the previously derived density function *d*(*m*), we can derive *F'* = *c*(*d*(*m*))

$$F'(m;q) = 754 + 65.7 \times 10^{6} \cdot \left(h^{-2.1}\right) \exp\left[2.1 \frac{\ln h - \ln 400}{q} \frac{m}{\overline{M}}\right].$$

where q is the percentage of the population that lives in neighborhoods with population densities greater than 400.

Finally, integrating this function gives a parameterization of the HFC network cost function at 5% capacity:

$$F(m) = 754m + \frac{65.7 \times 10^{6} \cdot \left(h^{-2.1}\right)}{2.1\left(\ln h - \ln 400\right)} q \cdot \overline{M} \cdot \exp\left[2.1 \frac{\ln h - \ln 400}{q} \frac{m}{\overline{M}}\right].$$

Regardless of how dense the city is, it costs a minimum of about \$760 to pass each house. For a low q city, few people live in high-density areas, and costs increase rapidly as one moves out from the city center.

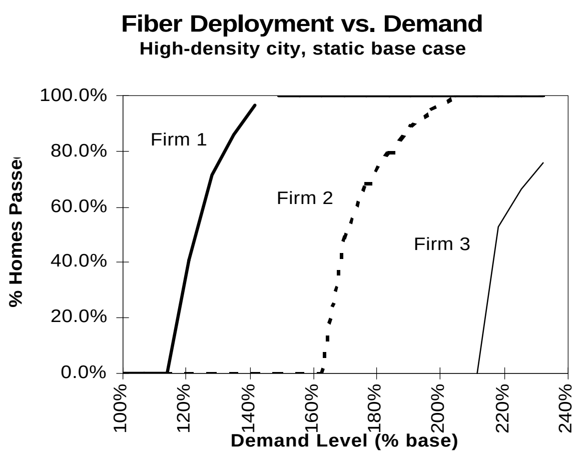
Capacity Costs Broadband services require, at a minimum, gateways to the Internet and account administration for each household. Very similar functions are already provided by Internet Service Providers (ISPs), and the ISP market appears to have reached a competitive equilibrium at $19.95 per month, $240 per year. Here it is assumed that $240 just covers all the above costs.

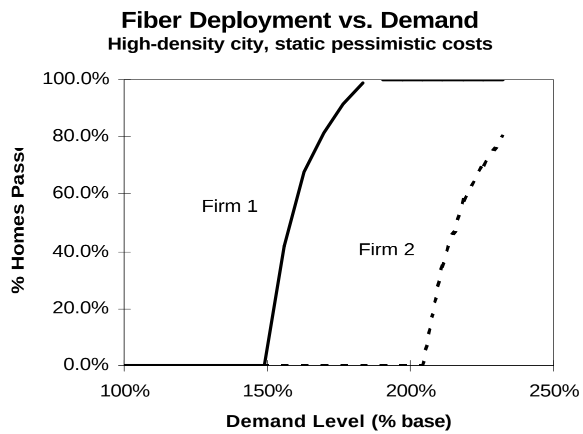
Fiber capacity costs are given in Jones and Shmania as service penetration ranges from 5% to 50%. These costs are largely independent of population density and are approximately $300 per additional house, or $30 per house per year at a discount rate of 10%. Based on these estimates, the marginal cost is set at c_F=$270 per year.

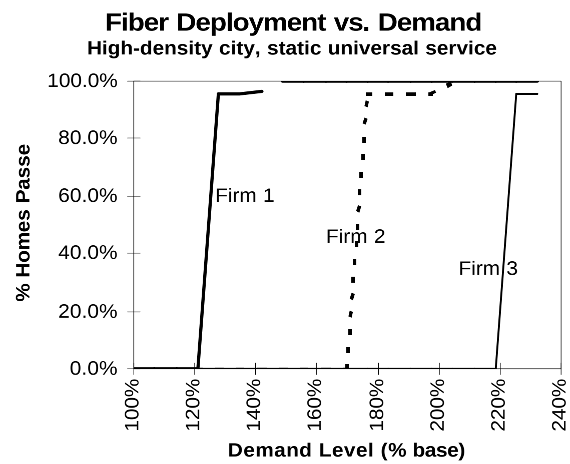
Omoigui et. al. also give costs for different penetration rates; using their estimates gives a convex marginal cost of between $248 and $315 per year over penetration levels of 5-50%.

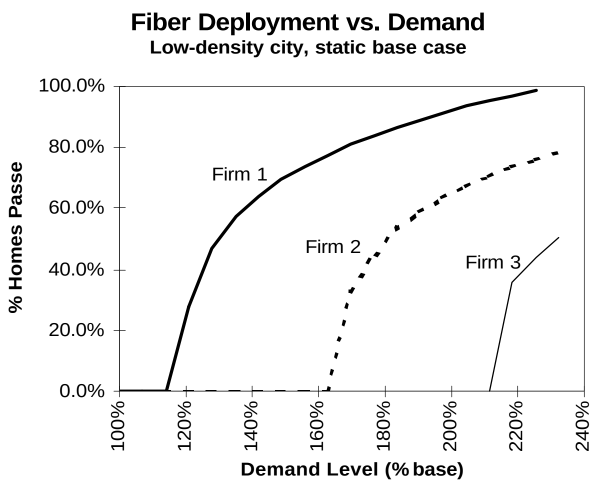
Appendix C - Competitive Broadband: Base Case vs. Pessimistic Cost Case vs. Universal Service Case

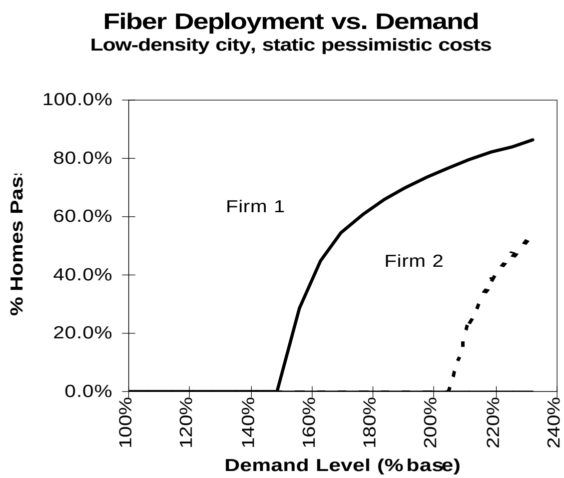
Fiber Deployment – High Density and Low Density Cities

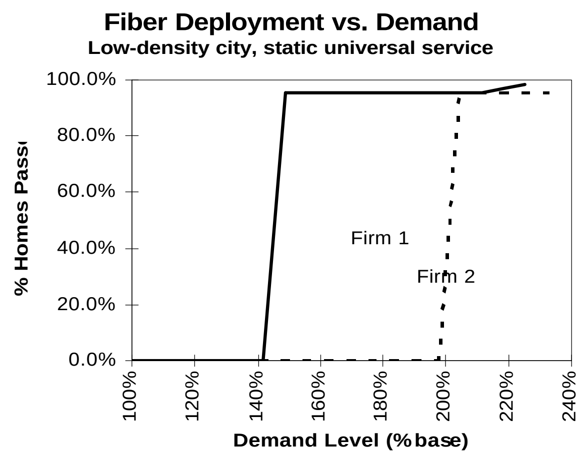




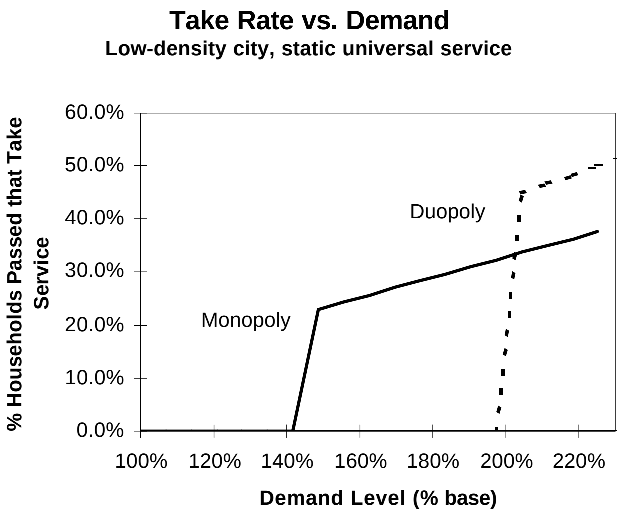


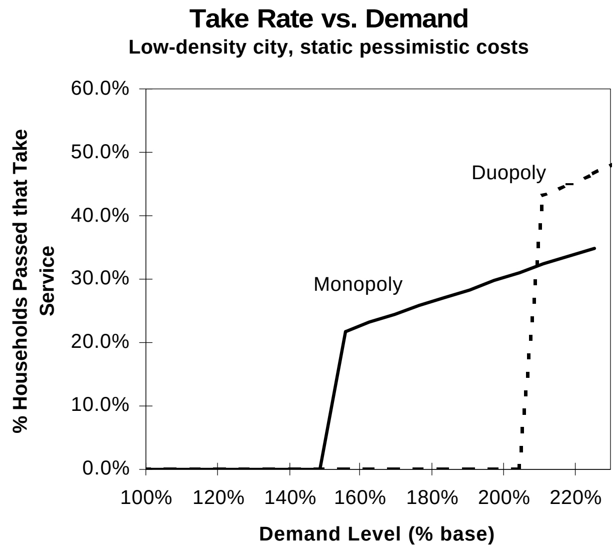


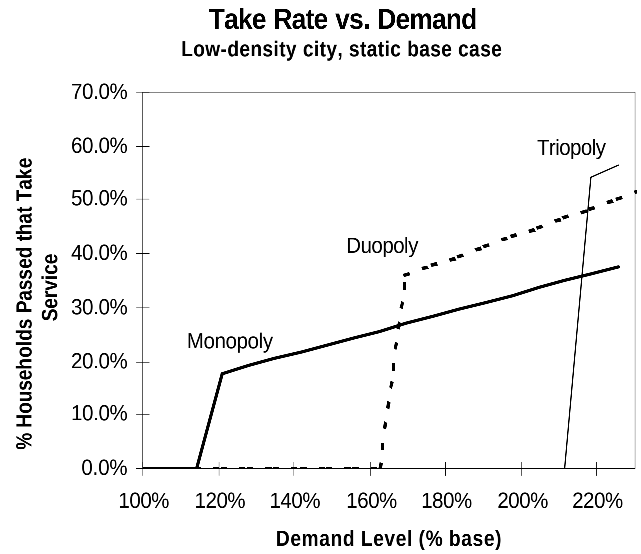


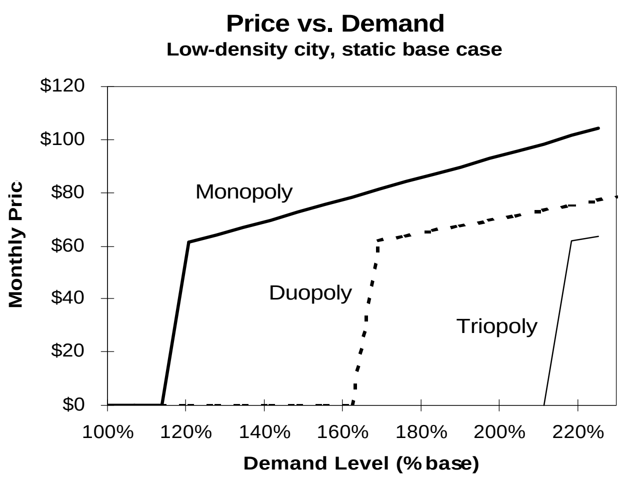


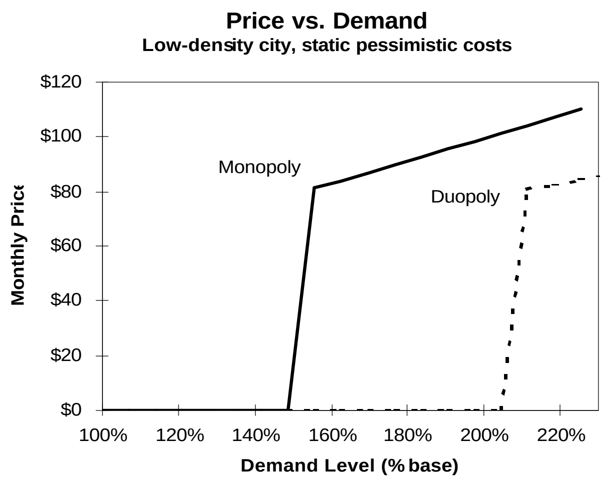
Quantities and Prices – Low Density City Only

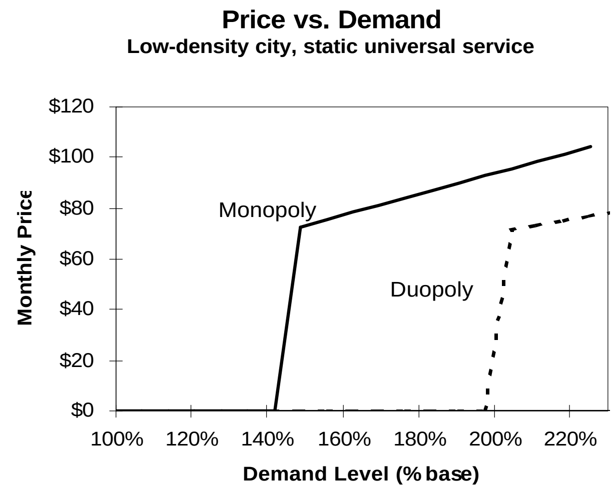




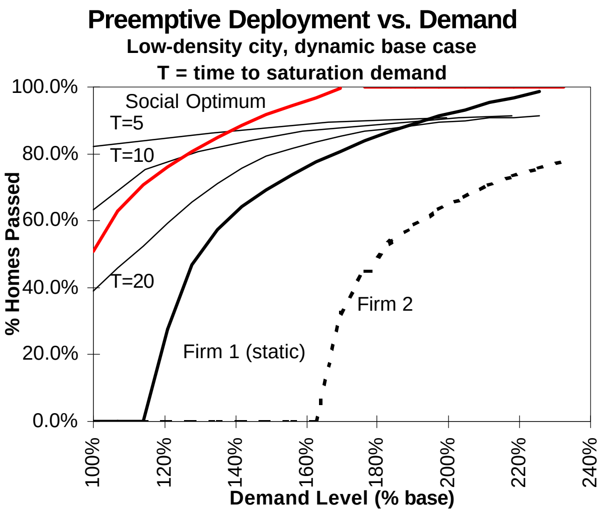


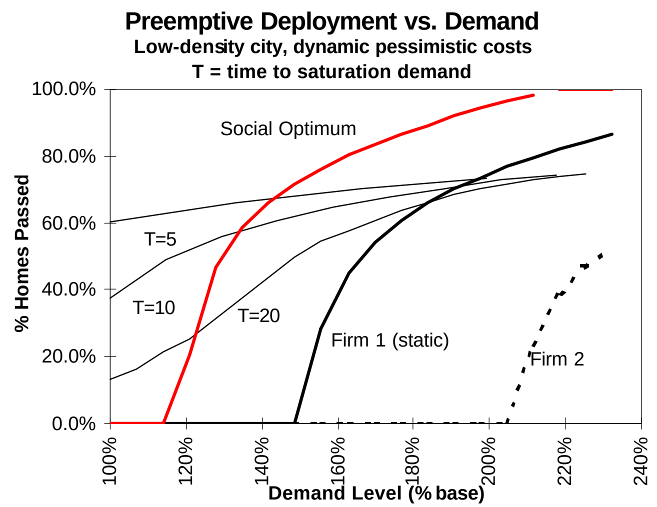


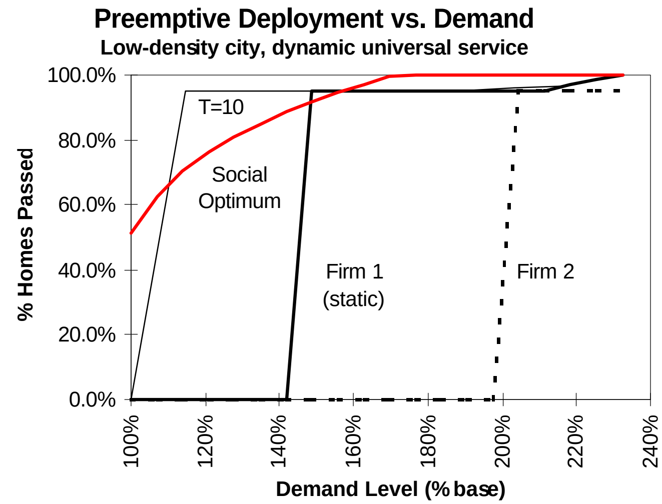


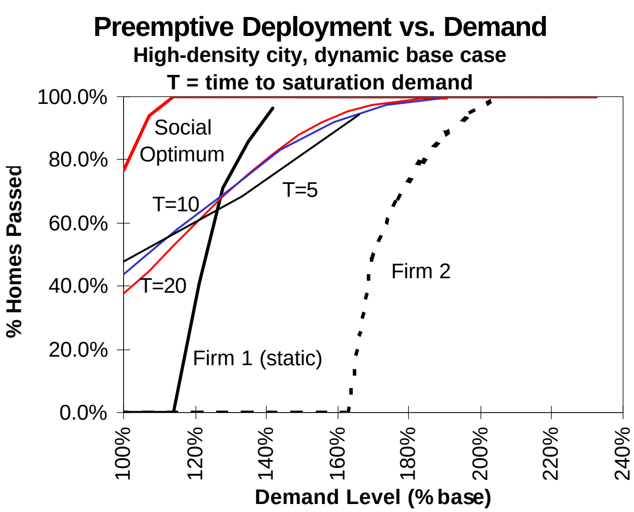


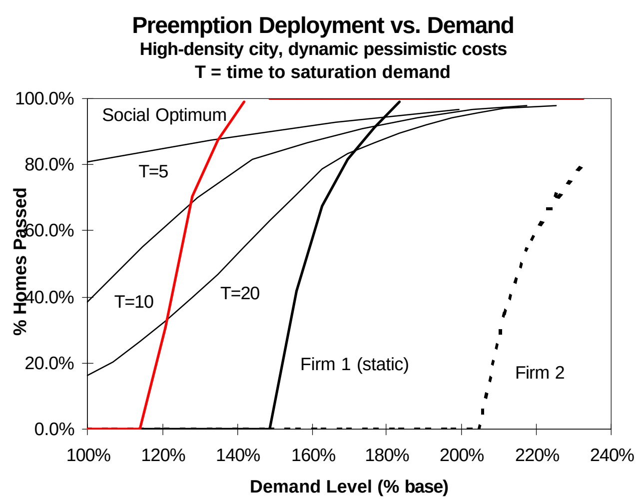
Dynamic Model – High and Low Density Cities
Deployment: Fast (T=5), Medium (T=10), Slow (T=20), and Social Optimum

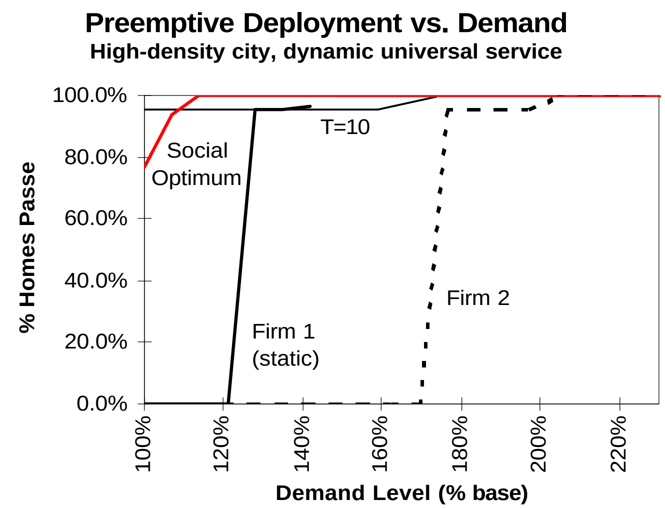












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-- Notes --

[1] By “interactive” we mean that the response of the system to a user request for information (say, a graphical screen, a picture, an application program, even a movie) is on the order of seconds, so that the user is actually interacting with the system, rather than sending requests for future delivery (such as a request to a library to send a copy of an article, which would take hours or days).

[2] The bandwidth of the access connection is not the only limiting factor to a speedy response over a data network. As with any network, Internet (indeed any broadband network) is subject to congestion; as usage increases, response times increase as more users compete for limited network bandwidth. Thus, even with broadband access to the network, fast response times are not guaranteed. If sufficient network capacity is not available, then network congestion can reduce response time considerably.

[3] With current modem technology, access connection speed is no more than 56 Kbps over a telephone line. By contrast, a typical corporate Ethernet connection is 10 Mbps.

[4] An exception is the US cellular and PCS telephone networks, which exist in each major city. While the frequencies that these wireless systems use are regulated (all radio frequency usage is allocated by the Federal Communications Commission) and therefore entry is regulated, prices are not regulated.

[5] Non-economic reasons have been advanced as well; networks “tie the country together,” yielding a social cohesion that is perceived as politically important; low-cost access to networks is viewed by some as a “right” of citizenship; etc. We do not consider these issues in this paper.

[6] In communications networks, this is often justified on economic grounds of a “network externality:” the more customers connected to the network, the more valuable it is to others already connected. However, the argument is also used as a political justification for universal service in situations with no network externality, such as cable television.

[7] These questions form the core issues discussed in the recent FCC report (Federal Communications Commission, 1999). Is broadband a natural monopoly? Will markets ensure universal service? Is regulation necessary? The results of our analysis appear to be consonant with the FCC’s findings in this report.

[8] In Section 2, we discuss the various technologies that could be deployed for broadband infrastructure. The two current contenders are cable modems (hybrid fiber-coax, or HFC, systems) and DSL (digital subscriber line, for use over existing telephone lines), each of which has been discussed extensively in the press. There is an emerging view (see Section 2) that HFC is superior in cost, bandwidth, and scalability. This is by no means a consensus, and telephone companies, who are the promoters of DSL, would strongly contest this view. It is our view that fiber/coax technology will dominate “medium-band” alternatives; therefore, HFC is the focus of this paper. There are two options for the use of fiber optic transmission media: hybrid fiber-coax (HFC), in which the last few feet into the home is coaxial cable, and fiber to the curb (FTTC). Both of these fiber technologies offer considerably more bandwidth than the abovementioned options, but both involve placing fiber in the ground wherever the provider wishes to offer service. The current consensus among engineers (see, e.g., Omoigui, Sirbu, Eldering & Himayat, 1996) is that HFC is the most cost-effective fiber technology, which is why we chose this technology as the basis of our analysis.

[9] Cost and demand analysis is necessary in order to draw conclusions regarding the likely structure of the broadband market. Currently, very few broadband systems are in place and operating, and all of these systems are

at the very earliest stages of development. Therefore, econometric cost and demand analysis is not feasible. We rely instead on calibration of our model using engineering cost estimates and demand estimates based on informal surveys.

[10] It is sometimes asserted that the marginal cost of a telephone call (or a single access to a Web page) is zero, except for the billing cost. This is true if (for some reason) there is excess capacity in the system or the usage occurs in an off-peak period, so that an extra unit of usage does not cause congestion. Otherwise, the long-run marginal cost of a unit of usage includes the cost of expanding capacity in order to handle this increased usage without increasing congestion. This is a marginal capacity cost, and is certainly not zero for actual networks.

[11] This is true of virtually all hard-wired electronic distribution networks, such as telephone, broadband, and cable television. Engineers refer to fiber channels that are not activated as "dark fiber," indicating that the modulation and terminal gear has not activated, or "lit," this optical transmission capacity.

[12] The three-part investment decision for broadband networks is very similar to that of other networked industries such as electricity and natural gas. In both industries there are "backbone networks" (electricity transmission and interstate natural gas pipelines) and local access networks (local electric utilities and gas companies) that must decide which households to pass. The natural monopoly and universal service arguments were used to justify monopoly franchises in these industries as well, although there were competitive overlay networks in the early stages of development.

[13] There may, however, be a network externality based on the aggregate number of broadband customers of all firms. Since such an effect would not change the inter-firm competitive environment, we do not include it in our model.

[14] Despite the interconnectivity of the Internet, America On-Line's lobbying efforts to secure resale rights on AT&T's @Home network ("AT&T Fights for Control in Struggle Over Internet Access," *New York Times,*Feb. 15, 1999) suggest that the bundling of infrastructure with ease of access and other customer servicesis important, particularly if consumers face substantial information and switching costs. We recognize the importance of these bundling and "portal" strategies to many Internet business plans. We believe that as Internet users become more familiar with the technology, these information and switching costs are likely to decline, making these advantages transitory.

[15] "The Battle for the Last Mile," *The Economist*, May 1, 1999.

[16] See, e.g., "Cable Modems Outpace ADSL," *Interactive Week*, July 31, 1998.

[17] It might appear that monotonicity of the density distribution is unlikely to hold for real metropolitan areas, with "edge cities" and other suburban developments. In fact, monotonicity is not required for the static model of this section. Assuming that connections to the Internet backbone network are equally available from most neighborhoods (see Federal Communications Commission, 1999, §§64-65 for evidence of this), then HFC costs, and therefore all strategies, depend only on density and not on distance. While the exposition and intuition of the model and its results is much clearer using the monotonicity assumption and its geographical interpretation, it is not essential for the results of the static model to obtain.

[18] In fact, we might expect neighborhoods within a city to show different demand characteristics, depending upon income and other factors. Households and neighborhoods with strong demand would, *ceteris paribus*, be more profitable for firms to serve, and thus attract more competition. In this model, we focus exclusively on density

differences that in turn imply a focus on cost differences (as we show below). Thus, differences in household profitability are assumed to derive only from these cost differences. Enriching the static model by including differing demand characteristics has the effect that the profitability of serving a household is now determined by two factors (demand and cost) rather than just one (cost), but is otherwise quite straightforward, and not worth the additional complexity and notation.

[19] The assumed convexity of network costs with increasing distance reflects the fact that as density of population decreases, the cost of passing a household with fiber increases dramatically.

[20] A rich set of pricing options are available to an access provider; since the current market model for ISP service appears to be a flat rate monthly charge for unlimited access, we assume a similar model for broadband access.

[21] Our interpretation is that all consumers have the same *probability* of taking service, which probability depends upon price. Of course, after the consumption decisions, some consumers will have taken the service and some will not, so *ex post* consumers will not appear to have the same preferences. We thank Joel Waldfogel for suggesting this interpretation.

[22] It is straightforward to show that coterminous service intervals are not a Nash equilibrium if firms are free to choose their intervals.

[23] If the constraint that $L(n) \leq M$ is binding, then firms $j = n,\ldots,1$ will all serve the entire metro area, and therefore will be completely symmetric. The asymmetry of the equilibrium applies to firms for which expansion to the metro area limit is not optimal.

[24] While this paper does not address collusion, the equilibrium suggests that one form collusion might take would be for firms to spread out and each take a separate monopoly area. Such a profile is not an equilibrium without some sort of exogenous punishment mechanism.

[25] Thompson, Maryann Jones, "Industry Spotlight: ISPs Struggle With Customer Growth," *The Industry Standard*, March 15, 1999.

[26] Current cable modem services do in fact charge monthly fees around \$50, but there are additional costs of setup, modem rental, and cable subscriptions ("Get Faster Access," *PC Magazine*, March 31, 1999). At these prices, take rates are around around 2% nationwide, but range from 10% to 25% in markets in which the service is well-established ("The Battle for the Last Mile," *The Economist*, May 1, 1999).

[27] $F(x)$ may be interpreted as the per period interest payment on an infinite bond that financed the construction of the network.

[28] In the high-density city, the saturation level of demand is high enough to support duopoly competition throughout the entire city. The monopoly area, $L(1)–L(2)$, is thus a transitory phenomenon that only appears while the market is growing. Nevertheless, the transitory profits from this area still induce preemptive building by the first mover, but this incentive to preempt is not a strong as in low-density cities, where the monopoly area has a much longer life.

[29] We use demand level on the horizontal axis rather than time in order to facilitate comparisons with the static model. Each growth scenario differs in the length of time required to reach the saturation level which is the rightmost point on the horizontal axis, beginning at the leftmost point.

[30] A similar result obtains as the discount rate is lowered, making the future more valuable.

[31] This is not a general result; in some simulations of the high-density city, the socially optimal network always is larger than the equilibrium network.

[32] Of course, the social optimum network has higher levels of consumption, corresponding to marginal cost prices, while the market scenario has duopoly and monopoly prices.

[33] We choose 400 people/mi^2 as a benchmark, because the engineering cost studies show that fiber deployment is relatively cheaper at densities at or above 400 people/mi^2.

[34] The estimates are Q=33% with P=\$50 per month and Q=10% with P=\$100 per month.

[35] Thompson, *op. cit*.

[36] Omoigui et. al. (1996) give cost estimates for a topology of 100 homes per mile, 16 homes per block. The assumptions about block layout used to make the conversion to homes per square mile were obtained from Omoigui (1995), and the number of people per home was assumed to be 2.6.

[37] Based on 60% analog video penetration, 1.6 set-tops per household, and a set-top cost of $125 plus installation cost of $50. See Omoigui et. al. (1996).