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THE MARKET STRUCTURE OF BROADBAND TELECOMMUNICATIONS*

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The recent growth of the Internet is creating markets for broadband telecommunications networks. In the past, virtually all such 'infrastructure' networks have been subject to government regulation. Two reasons advanced for this market intervention are (i) such networks constitute a natural monopoly, and (ii) to achieve 'universal service', in which all citizens have access to services. In this paper, we develop a model and estimate it using engineering data which tests if these two hypotheses are likely to obtain for broadband networks. We find that oligopolistic competition is likely to emerge for demand levels approaching that of today's cable television.

I. INTRODUCTION

THE RECENT POPULARITY OF THE INTERNET and World Wide Web with both consumers and firms is creating markets for information services that require telecommunications networks capable of interactive high-speed data transfers. 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.

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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 voice telephone service using a transfer rate of approximately 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

[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.

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

[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.

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 two scenarios: (i) a model in which firms decide to enter, choose the scope of their network, build capacity and offer service; and (ii) a 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).[10] As discussed below, we consider a range of demand levels, from a fairly modest base level of 15% household penetration to a more mature cable TV-like penetration of 67% of US households.

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,

[7] These questions form the core issues discussed in the recent FCC reports (Federal Communications Commission [1999a], [1999b]). 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 these reports.

[8] In Section II, 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 II) 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 *et al.* [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] In related work, Hogendorn [2000] considers 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. The results of this analysis are discussed below.

the discipline of model building and data calibration may permit us to emphasize 'informed' over 'guesses', and make the results worthy of some attention.

Using US household density data, we find that:

(i) broadband deployment is profitable in both high-density and low-density cities at demand levels about 7%–20% higher than base 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) competitive entry occurs for demand levels 50%–70% greater than base demand levels.
(iv) the universal service regime leads to fewer competitors in the market at some demand levels; under our 'pessimistic cost' assumptions, only one firm serves the mature market; in this case, the universal service mandate actually creates an artificial 'natural' monopoly.

In Section II, the cost structure of communications networks is discussed; in Section III, the market model is developed, and equilibrium conditions derived. In Section IV, engineering estimates of cost and the parametric estimates of demand are used to derive expected market outcomes. Section V summarizes the conclusions that follow from the analysis.

II. 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[11] (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 which homes and businesses to pass with such lines would determine its target market. However, simply laying the cable does not connect the homes so passed. If a home or business wished to be

[11] 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.

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.[12] 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 which households to pass with the network (i.e., which target markets it wishes to serve).

It is this network investment decision that makes broadband networks, indeed most network infrastructure, a unique problem.[13] Once a network is built with a specific 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 market equilibrium results of Section III.

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 is likely to be the incumbent cable company. However, an upgrade of a cable network to two-way HFC requires substantial capital expenditures, so any cost advantage is most likely less than it might initially appear. To save notation and complexity, we present our model with symmetric costs

[12] 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.

[13] 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.

for all firms. At the end of Section III, we discuss how adding a cost advantage would produce only slight changes in the equilibrium outcome.

The other available broadband technologies currently cannot offer the same bandwidth as HFC at a comparable cost (Omoigui *et al.* [1996]), or to all customers. Current implementations of digital subscriber line (DSL, an enhancement of traditional twisted-pair copper telephone lines) only work on telephone lines less than 15,000 feet from the central office, and only those that do not use digital line carrier (DLC).[14] Direct broadcast satellite (DBS) typically provides around 400 Kbps one-way bandwidth, but cannot provide a satellite return path (*Economist*, [1999]). There are some promising new technologies, including higher speed DSL, 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,[15] 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.[16]

III. A MODEL OF COMPETITION IN COMMUNICATIONS NETWORKS

The model is formulated to focus on the firm's network investment decision of which households to pass with broadband networks. The costs of passing a home with a broadband network are highly sensitive to the population density of the area surrounding the home. Houses and other buildings that are spread further apart require more cabling and, because signal strength and quality decline over distance, more electronic components. In order to focus on the cost aspect of the scope of network deployment, we assume that households differ only in their density attribute, but in all other respects are identical: hookup cost, cost of traffic capacity (switches and routers), and demand characteristics are the same for all households.

Firms compete in a three-stage game, where each stage represents one of the infrastructure investment decisions: which households to pass, how much traffic capacity to install, how many households to hook up. Where

[14] In the case of US West, a US Regional Bell Operating Company, only 36% of their subscriber lines were DSL-capable (as reported in Brown [1999]).

[15] The current evidence of HFC superiority over DSL, based on early market deployment in 1999, seems very strong (see, e.g., Quinton [1999], Flanagan [1999], and Greene [1999]).

[16] As the demand for capacity increases with increasing usage, both cable firms and telephone companies offering DSL will have to extend their fiber optic plant closer to homes. Eventually, both technologies should converge to full fiber to the curb (FTTC), assuming they both survive to this very long run future.

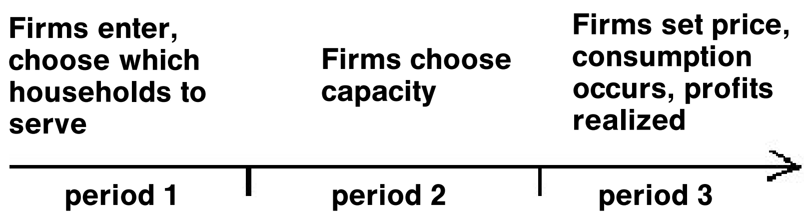

Figure 1

the structure of the universal service scenario differs, the differences are described.

The Game

There are M households located in neighborhood settings that determine the expense of building a broadband network to serve them. 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 $m \in 1, \dots, M$ be given by d_m. We assume all households in the city have identical preferences for broadband services; households only differ in their density attribute.[17]

A large number of identical firms may offer broadband access services to these households. They play a three-stage game, the timing of which is shown in Figure 1. The results of each stage are revealed to all.

Stage 1: Which Households to Serve

In the first stage, identical firms decide whether to build a network and which households they want to serve. Let the number of firms that enter be N, and let each firm choose a service area for its network. The service area is a set of households A_i, where $i = 1, \dots, N$ indexes the firms. We expect that each A_i will be made up of one or more subsets, each of which

[17] 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.

will be composed of contiguously located homes. (Such subsets would likely correspond to what engineers call a 'node' in the network; 500-home nodes are a typical size.) However, we make no geographical assumptions or constraints in this model, so each A_i may be composed of any subset of the M households.

Let $f(d)$ be the marginal cost of constructing a broadband network that passes a household with density attribute d. This marginal cost will be decreasing in d, reflecting that fact that the cost per home passed of a fiber network is lower in high density areas where houses are close together than in low density areas. A firm's total cost of building a network throughout its chosen service area is

$$F(A_i) = \sum_{m \in A_i} f(d_m)$$

This choice of which households to serve 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. A crucial result of the network building is that some households may be located in the service areas of more than one network. These households would have access to a competitive choice of networks. Other households might not be located in any of the service areas and would therefore be unable to obtain broadband access.

Stage 2: Traffic Capacity Choice

In the second stage, firms choose traffic capacity (size of routers, switches, portion of fiber to 'light', etc.) for their networks; this capacity choice determines the maximum percentage of households passed that can be served in the final stage.

The ability of firms to commit to traffic capacity decisions is very important to the type of competition that emerges in equilibrium. Ultimately, once the network is built and provisioned with electronic gear, the marginal cost of transmitting data is essentially zero. This property leads to a natural supposition that some form of very intense, Bertrand competition would take place, at least in the static oligopoly setting that we consider here. It is the choice of traffic capacity that introduces a barrier to this style of competition, since extensive price cuts would lead to capacity shortages.

Firms may install different traffic capacities relating to different households. Let firm i's traffic capacity choice relating to household m be denoted $z_i(m)$. This capacity is expressed as a fraction, and indicates the percentage of households in the immediate vicinity of m for which the network has capacity to offer service. The cost of this capacity is s per household. At the end of the second stage, all capacity decisions become common knowledge.

Stage 3: Pricing and Consumption

In the third stage, firms choose prices 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 to different households. However, firms cannot observe individual demand curves, so this ability does not allow price discrimination. What it does allow is for firms to respond to the competitive environment of each house, setting different prices for houses that have access to varying numbers of networks. Let $p_i(m)$ be firm i's price charged to household m; this price includes unlimited broadband service.[18] Let $\mathbf{p}(m)$ be the vector of price charged by all different firms for which household m is in their service areas.

The probability that household m demands a connection from firm i is denoted $q_i(\mathbf{p}(m))$.[19] 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 $q_i(\mathbf{p}(m)) \leq z_i(m)$. The cost to connect and serve a household is c that includes billing and any Internet charges levied on a per user basis. Again, price decisions become common knowledge.

It is important to reiterate a household's demand probability and the costs of both network capacity and hookups are not dependent on activity of adjoining households. 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.[20]

[18] 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.

[19] 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.

[20] Goolsbee and Klenow [1999] find fairly strong network externalities in computer adoption within communities, and link it to Internet and e-mail usage. This suggests that the decision to purchase a computer and get online may indeed have strong neighborhood effects. However, the decision to purchase broadband service is likely to be subsequent to a positive computer purchase/e-mail decision; further, the neighborhood effect that Goolsbee and Klenow find appears e-mail-centered, a service which is just as effective on narrowband as on broadband. This suggest that the neighborhood effects they find are not likely to impinge on the broadband purchase decision.

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 at the level of the household. Second, the strategies for each household are shown to be dependent only on the number of firms offering service to that household. Third, it is shown that households with different density attributes will, in equilibrium, be served by different numbers of firms.

Cournot Competition

In the second and third stages of the game, the sets of households passed by each firm are already determined and therefore the number of firms passing each house is known to all. The traffic capacity and price subgames are thus played on a house-by-house basis.

It is worth stating a result that follows immediately from our assumptions but is perhaps not totally obvious: the subgame equilibrium traffic capacity and price strategies depend only on the number of networks to which a household has access.

The intuition behind this result is that (i) all network costs are sunk by the final two stages of the game, so these costs do not enter into pricing decisions; (ii) all consumers have identical demand characteristics; and (iii) all firms face the same costs (capacity and marginal) and demands. Therefore, the only property that differs across households is the number of firms whose networks pass the household.

For each household, the firms simultaneously choose traffic 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. Note again that the necessity to install capacity constrains overly aggressive price cutting in Bertrand competition that may be suggested by close-to-zero marginal operating costs.

Friedman [1988] extended the analysis to games with many firms 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 $s + c$.

Proof. Straightforward application of the Friedman [1988] results.

The subgame equilibrium prices and quantities that emerge from stages 2 and 3 are denoted $p(n)$ and $q(n)$ where n is the number of firms that pass a particular household. The equilibrium strategies are identical for all firms because of the assumption that all firms have symmetric demand and cost characteristics.

Subgame Equilibrium for Entry and Service Area Decisions

In the first stage, firms decide sequentially whether or not to enter, and if they enter which households will be included in their service area. This determines how many firms pass each individual house. Firms expect Cournot prices and quantities for each household as shown above. In equilibrium,

- Each firm will choose the service area 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 a household for which operating profits are larger than network investment costs, given existing and anticipated competition.

Let the operating profit per household when n firms' networks pass that household be given by

$$\pi(n) = (p(n) - s - c)q(n)$$

Definition. For given n, let $L(n)$ be the lower limit of the density attribute at which the operating profit for each of the n firms derived from passing (and potentially serving) a household with that density is exactly equal to the marginal cost of constructing a network past that household. Then $L(n)$ solves

$$\pi(n) = f(L(n)) \quad n = 1, 2, 3, \ldots$$

Because the f function is monotonic negative in density, a unique solution to this equation always exists and $L(n)$ is increasing in n. Note that $L(1)$ may exceed the highest density attribute of any household in the market, indicating that zero firms is the equilibrium. Let δ be the highest population density actually observed among the M households. Recall that firms are indexed by the order in which they enter and build their network.

Proposition 2. If $L(1) < \delta$, then in equilibrium, the number of firms in the market $N > 0$ satisfies $\pi(N) - f(\delta) \geq 0 > \pi(N+1) - f(\delta)$. For $n = 1, \ldots, N$, the nth firm to enter the market serves all households with density attributes in the interval $[L(n), \delta]$. This equilibrium is unique.

Proof. See Appendix A.

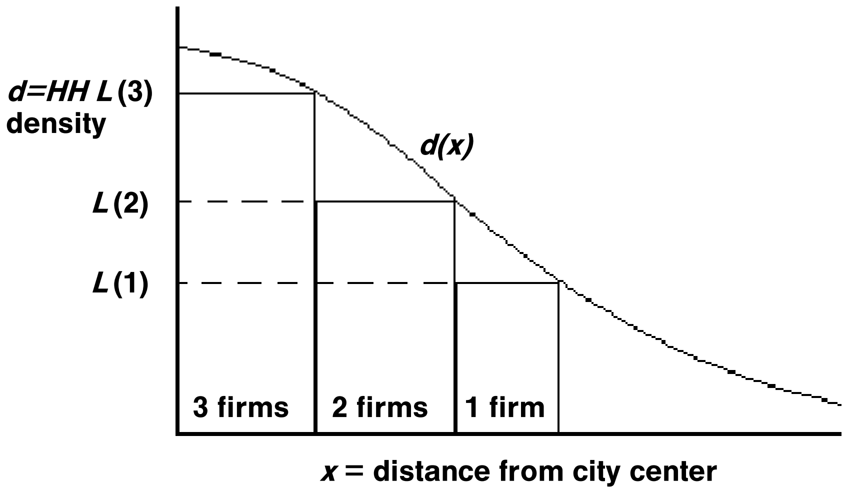

Figure 2

Corollary. Households with density levels in the interval $[L(n+1), L(n)]$ are passed by exactly n firms.

Note that although all firms are identical, the equilibrium is not symmetric.[21] The households with the highest density attributes support the most firms, the next most dense households support one less firm, and so forth, until $L(1)$, below which no firm builds a network and no service is offered.[22]

The asymmetric outcome of this model contrasts sharply with the more traditional location models. What drives this difference is that the distribution of households is both exogenous and asymmetric. That is, households do not move as a result of price and availability of broadband, and the cost per household is a function of density, which is not the same for all households.

By way of illustration, consider a hypothetical city which is radially symmetric. Let a household located at distance x from the city center have density attribute $d(x)$, where d is monotonically decreasing in x. Figure 2

[21] It is straightforward to show that a strategy of avoiding overbuild competition is not a Nash equilibrium.

[22] If the constraint that $L(n) \leq M$ is binding, then firms $j = 1, \ldots, n$ 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.

shows a possible equilibrium set of location decisions with three firms along a radius of this (symmetrical) city.

An Aside: Network Location Decision with a Universal Service Constraint

Suppose the households are reordered so that $d_1 \geq d_2 \geq d_3 \geq \ldots \geq d_M$. If there is a universal service franchise requirement on entering firms to pass some fraction φ of the households in a particular market (a city, county, region, etc.) then firms are constrained to serve all households with densities greater than or equal to $d_{\varphi M}$. Denote by $\Pi(n, d)$ the total profits of each of n firms which all build networks passing every house with density levels greater than d:

$$\Pi(n, d) = \sum_{m \in \{d_m > d\}} (\pi(n) - f(x))$$

Then the limit density level for n firms under the universal service constraint is

$$L_\varphi(n) = \begin{cases} L(n) & \text{if } L(n) \leq d_{\varphi M} \\ d_{\varphi M} & \text{if } L(n) > d_{\varphi M} \text{ and } \Pi(n, d_{\varphi M}) \geq 0 \\ \infty & \text{if } L(n) > d_{\varphi M} \text{ and } \Pi(n, d_{\varphi M}) < 0 \end{cases}$$

The total number of firms N that enter with a universal service franchise requirement satisfies $L_\varphi(N) \leq d_1 < L_\varphi(N+1)$.

Cost Advantages to 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. In this sense, the model presented above is conservative; if *de novo* entry is feasible, how much more so if there is an advantage of incumbency. This section discusses the effect of a cost advantage on the equilibrium.

The most important source of incumbency advantage is likely to be in network construction and in fixed entry costs.[23] While all incumbents' networks require upgrading, certainly some structures such as incumbent-owned underground conduits or rights-of-way can be shared with existing services, yielding same cost advantage. Further, the fixed entry cost for an

[23] Operating costs are principally customer billing, a function that today's ISPs are able to undertake within the $13–$20 per month per subscriber fee they charge; it is unlikely that an incumbent's pre-existing billing system would constitute a major cost advantage. Similarly, it is unlikely that a cable firm would have any advantage in providing traffic capacity in the form of switches and routers, since these are not currently used to provide cable service. Thus, we may ignore these costs as a source of incumbency advantage.

existing firm may be lower, particularly if it possesses a favorable brand presence. However, neither a network construction advantage nor a fixed entry cost advantage would change the amount of operating profit earned by any of the firms from a given household, but it would allow the incumbent to serve profitably households with lower densities than an entrant firm could serve. In effect, the $L(1)$ limit would be shifted to a lower density. Because the entrant firms would have identical costs and operating profits as in the original model, the limits $L(2) \ldots L(N)$ would not be shifted.[24]

The result of the cost advantage is that the incumbent would serve lower density households than otherwise, but any entrant firms would face the same incentives to enter as they would without the cost advantage. Thus, the cost advantage would be unambiguously welfare-improving. The incumbent firms would make higher profits, more households would have access to broadband, and the amount and extent of competition would not be diminished.

Since a cost advantage, should it exist, would improve the prospects for broadband deployment, we have chosen the more conservative and computationally simpler assumption that all firms face symmetric costs in our simulations.

IV. 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 are in their earliest stages of commercial deployment, 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 III using engineering

[24] We note that the costs considered here are those of *physical* capital, which by no means captures the full extent of actual costs faced by real firms. It is clear that the emerging broadband market is rather different from either the extant cable TV market or the extant local telephone market. Therefore, both the *human* capital and the *institutional* capital in these two industries is unlikely to be well-suited to recognize and exploit opportunities in broadband. Neither the management nor operational talents of these two industries are necessarily well matched to this market. Further, each industry is currently publicly regulated (local franchise for cable, state/Federal regulation for telephone) in ways that appear to be a poor fit with the emerging broadband market. It is our view that these factors constitute a fairly substantial *disadvantage* of incumbency, which likely outweighs whatever cost advantage accrues from the ownership of physical assets that are only partially suited to the task of transmitting two-way broadband signals.

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 (network 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 consists of a set of households with identical demand characteristics that differ only in their density attribute.

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 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 (Thompson [1999]), typically for Internet service at \$20/month, so this would appear a realistic baseline.[25] Our 'mature market' demand level corresponds to 66% of households taking broadband at \$50/month; this is about the take rate for cable TV today, a mature electronic distribution product.[26]
(iv) The distribution of household density is that of the US population as a whole. This density is derived from the US Census Bureau STF3A data tapes, Census Tract level data.

[25] Current cable modem services do in fact charge monthly fees around \$50, but there are additional costs of setup, modem rental, and cable subscriptions (Derfler and Freed [1999]). At these prices, take rates are around 2% nationwide, but range from 10% to 25% in markets in which the service is well-established (*Economist* [1999]).

[26] As noted above, there is considerable disagreement about the price elasticity of demand, with our estimate of −1.533 on the high end (in absolute value) of the range of estimates (see, for example, Rappaport *et al.* [1997]). The model was also estimated using an elasticity of −0.5; our finding was that to a first-order approximation this is equivalent to increasing the demand intercept by about 80%. Therefore, in the context of our linear demand model, our assumption of rather elastic demand yields conservative results in terms of speed of deployment.

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 to the mature market demand (see above). 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%.

For the above range of demand levels, the calibrated model was solved for scope of the network ('buildout'), price and quantity (take rate), for both the unconstrained market equilibrium and the constrained universal service mandate equilibrium. To test the sensitivity of the results to the calibration assumptions, we also solved the model assuming network costs were 50% greater than the base ('pessimistic costs').

In Appendix C, the results of are presented in graphs. The following equilibrium quantities are plotted as a function of the demand level:

(i) Fraction of households passed (network scope), for each firm; for both the unconstrained market and the universal franchise market (Figure 3).
(ii) Quantity demanded ('take rate') in each market area (valid for both scenarios) (Figure 4).
(iii) Prices in each market area (valid for both scenarios) (Figure 5).
(iv) Fraction of households passed (network scope), for each firm, with network costs assumed 50% greater than base; both unconstrained market and universal franchise market (Figure 6).

Results of the Analysis

The results of the scenario analysis are

Network scope issues: Initial entry occurs at a demand level about 7% above base demand. This appears consonant with efforts by several firms to enter the market in the current year. At a demand level 50% above base, two firms compete for the densest markets; the less dense are served by a monopoly. At a demand level 85% above base, three firms enter the market. At a demand level about that of today's cable TV, over 87% of households have broadband available from at least one provider, and about 70% of households have a choice of three providers (Figure 3).

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 (Figures 4–5).

Cost Assumptions issues: For pessimistic costs, the profile of market-structure growth looks much the same, but less entry and more delayed; initial entry is at a demand level 25% above base, and a duopoly emerges at 75% above base. At a mature demand level, there are again three providers, but the network scope is less than in the base case.

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. In the base case, this does not happen. Entry is in fact delayed to a demand level 50% above base, and competition occurs at 100% above base. However, under the pessimistic cost assumption, competition does not emerge within the demand range studied; initial entry occurs at 75% above base demand (Figures 3–6).

V. 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 provisional 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.

The form of competition is asymmetric, with dense areas having more competitive options than sparse areas.

If costs are greater than anticipated, entry of firms into the market is delayed, and competition is lessened. However, the model suggests that entry by multiple firms can be supported at higher demand levels even if our cost estimates are significant underestimates.

Universal Service It appears that the unconstrained market can bring broadband to almost 90% of US households, suggesting that as the market matures most US households will have broadband available. Requiring that all entrants pass 95% of households adds substantially to network costs, making entry more expensive. Imposing a universal service mandate on all entrants, however, significantly retards deployment and retards competitive entry as well. In the pessimistic cost case, the universal service mandate becomes so expensive as to preclude competition.

In the Base Case, this delays entry, and delays competition, but it does not eliminate it. For the Pessimistic Cost case, however, no entry occurs even at high levels of demand. Thus, imposition of a universal service mandate actually creates an artificial (as opposed to natural) monopoly.

Timing of Competitive Entry This paper is concerned with comparing static equilibrium outcomes at different (static) demand levels, and not about demand growth. However, it is plausible that demand growth will occur, and that in the early stages of growth only a single firm will be in the market. Our model suggests that duopoly can only be supported at higher levels of demand, but that in a mature market, this industry is not a natural monopoly. However, during the period of growth, 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 and regulatory forbearance 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 within the context of a specific static oligopoly model. 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 infrastructure 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.

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.

Dynamic Equilibrium An obvious problem with our static model is that it cannot capture demand growth and possible strategic behavior by first movers. In related work, Hogendorn [2000] considers such a dynamic model, similar in structure to the model of this paper, and finds that a first mover may indeed preempt by overbuilding its network (relative to the static equilibrium) in order to capture future rents of being the larger network. Thus, future rents are partially dissipated by aggressively expanding network scope, a form of preemption that is (generally) welfare-improving for consumers.

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. 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 serves all households with densities $L(n) \leq d \leq \delta$. Suppose firm n chose not to serve some household a with $d_a > L(n)$. The change in profit from this deviation is

$$-\pi(n) + f(d_a)$$

From the definition of $L(n)$ this change in profit is negative for any $d_a > L(n)$. Therefore any deviation that result in the firm not serving a household with density greater than $L(n)$ decreases the firm's profits.

Suppose now that firm n chooses to serve some household b with $d_b < L(n)$. The change in profit from this deviation is

$$\pi(n) - f(d_b)$$

From the definition of $L(n)$ this change in profit is negative for any $d_b < L(n)$, so any deviation that results in the firm serving a household with density less than $L(n)$ decreases the firm's profits.

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 serving some set of households A_j. Suppose some household is density in the interval $[L(n), \delta]$ is passed by fewer than n firms. Then from the definition of $L(n)$, an additional firm could increase its profits by serving this house. Therefore no equilibrium can have less than n firms serving households with densities in $[L(n), \delta]$.

Suppose that some household with density in the interval $[0, L(n)]$ is passed by more than n firms. Then from the definition of $L(n)$, at least one of these firms could increase its profits by not serving that household. Therefore, no equilibrium can have more than n firms serving households with densities in $[0, L(n)]$.

Thus, all Nash equilibria are characterized by n firms building networks to serve all houses with densities in the intervals $[L(n+1), L(n)]$, $n = 1, \ldots, K$. Further, if $K < N$, then and entrant serving all houses in the interval $[L(K+1), \delta]$ would be 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.

APPENDIX B

Calibration of the Model from Existing Data Sources

Demand This analysis uses a linear demand curve: $P(Q) = \alpha - \beta Q$. 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.[27] According to this estimate, $\alpha = 120$ and $\beta = 217.42$.

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

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 (Thompson [1999]), 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 base demand level, we assume that half of these online households would purchase broadband service at \$50.00 per month: $Q = 0.15, P = \$50$. At these prices, demand elasticity for broadband is about -1.533 (estimated by Mohan [1994]), although there is disagreement concerning this (see Federal Communications Commission [1999a], fn.260), where demand is alleged to be less elastic. We adopt the assumption of more elastic demand as we believe that narrowband services will continue to be a major factor in the Internet access market for many years (see Federal Communications Commission [1999b], p. 23 and Appendix A), and will provide substantial competition to broadband for many customers.

We shift the demand curve to intersect this base demand point, which results in $\alpha = 82.5$. 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: $Q = 0.66, P = \$50$. Shifting the demand curve to intersect this point results in $\alpha = 194$, or 235% of the assumed base demand level. In the analysis, we vary α in order to examine the sensitivity of the results to demand variation.

Costs Cost estimates are needed for both the network costs of installing cables and associated hardware and for the capacity costs of installing terminal equipment and hookups for individual houses.

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

These studies discuss several different network types. The one that seems to best represent the general-purpose broadband networks discussed in this paper consists of 500 home nodes, 25% peak coincident usage, with 2.85 Mbps available to each home during this peak usage.

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.

Jones and Shmania present cost estimates at six different population densities, form 200 to 1,400 people per square mile. Because much of the rural population lives at densities under 200 per square mile, we have fit the data to a curve and extrapolate the cost per home passed in low-density areas. We chose the functional form $c(d) = A + Bd^{\gamma}$, where d is the population density.

We fix the exponent, γ, at -1. This implies that if density is cut in half, the density-related portion of cost per home passed doubles. This is a fairly strong (and conservative) assumption, in that it implies that cabling costs depend only on area covered and not on number of households. Should the number of households matter, then the exponent γ would be greater than -1 and it would be relatively less costly to serve less dense areas. From an engineering perspective, this strong assumption is likely to be true for low-density areas, since the ability to share equipment among households is limited by the distance signals must travel. At low densities, building a network on a road with X houses costs the same as building a network on a similar-length road with $\frac{1}{2}X$ houses. The actual best fit *within* the range of densities given by Jones and Shmania is $\gamma = -2.1$, but $\gamma = -1$ provides a stronger engineering motivation for obtaining accurate extrapolations *outside* that range.

The best fit of the Jones and Shmania estimates to the curve $c(d) = A + Bd^{-1}$ is

$$c(d) = 581.7 + 200{,}354.9d^{-1}$$

with $R^2 = 0.955$.

In comparison, the Omoigui estimates only consider a density of 1,600 per square mile and are about 16% higher. To account for the possibility that network costs will be higher, we have included a scenario that uses the above curve fit but multiplied it by 150%.

We also fit these coefficients assuming $d = -0.75$, a more optimistic cost assumption regarding low-density deployment costs. The simulation results are quite similar, except that deployment occurs at lower demand levels than with $d = -1.0$. We report the more conservative results.

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 \$20 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%.

Household Density The results of this model are driven by differences in household density; denser areas are less costly to serve and in equilibrium are offered more competitive options, while less dense areas are more costly and are offered fewer, if any, options. Therefore, calibrating density differences is critical to the credibility of the results. Our density distribution is derived directly from the US Census Bureau STF3A data tapes for 1990, by Census Tract. This data includes number of households and area in square miles for each of over 60,000 US Census Tracts. This empirical distribution is what we use in the simulations.

APPENDIX C: COMPETITIVE BROADBAND

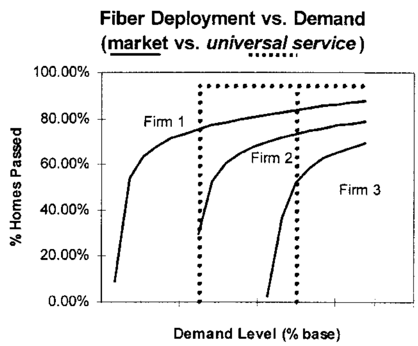

Figure 3

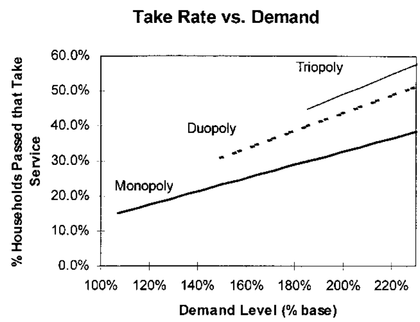

Figure 4

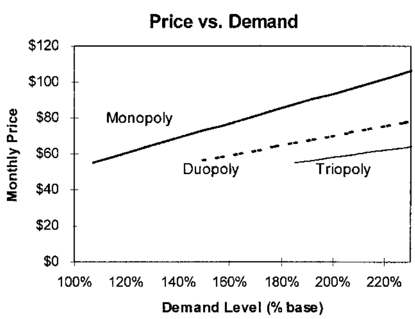

Figure 5

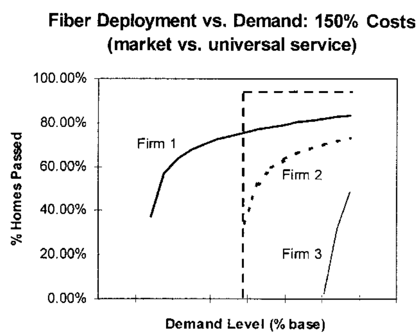

Figure 6

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