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Abstract

We document entry and capacity expansion in US long-distance fiber-optic networks before and during the "telecom boom." We disentangle the many swaps and leases between networks in order to measure owned route miles versus route miles shared with other carriers. Entry appears much more moderate when these shared miles are not counted. Strategic behavior can lead to excessive entry, and we find evidence of such behavior regarding total miles (including swaps and leases) but not regarding owned miles. We conclude that entry was excessive only with regard to swaps and leases, but not with regard to the physical building of the networks.

JEL classification: L11, L13, L96

Keywords: telecommunications, investment, preemption

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1 Introduction

During the late 1990s there was tremendous capacity expansion and entry of new firms in the North American long-haul telecommunications industry. These expansions were driven by very fast demand growth for Internet and other data-oriented telecom services and by exponential decreases in the cost per bit transmitted using fiber optic communications equipment. But by 2001, competition and slowing demand growth were squeezing the profits of these carriers, and an equally unprecedented slowdown in spending occurred. The problems in the telecommunications sector have been blamed for dragging down growth in the entire U.S. economy.

As the expansion turned to bust, discussion of "excessive entry" and a "fiber glut" became increasingly common. Generally the fiber glut story revolves around three premises. First, Internet growth was not as fast as expected, and in particular, not as fast as Worldcom claimed (Odlyzko 2003). Second, the still-high growth rate of data traffic was "...not nearly fast enough to use all of the millions of miles of fiber-optic lines that were buried beneath streets and oceans in the late-1990s frenzy."[1] Third, the equipment used to send data over fiber optic cable improved dramatically so that each strand of fiber could carry many more gigabits of data: "Perhaps never before has the efficiency of an industry's technology gotten so far ahead of demand."[2]

These gloomy statements have become the conventional wisdom: there was excessive entry of fiber optic networks based on overoptimism and strategic behavior. In this paper, we analyze whether this conventional wisdom is correct based on new data we have collected. Our data distinguish between sunk investments (actual miles of right-of-way) and non-sunk investments (relatively fungible swaps and leases of conduit space and fiber). We also run empirical tests for strategic behavior that might lead to *ex post* unprofitable networks. We find that more than half of the entry was non-sunk investment, and evidence for strategic behavior is largely limited to these non-sunk investments. We conclude that the "excessive" label is applicable only to these swaps and leases.

Before moving further, let us clarify the industry segment we are discussing. The national fiber-

[1] Yochi Dreazen, "Behind the Fiber Glut – Telecom Carriers Were Driven By Wildly Optimistic Data on Internet's Growth Rate," *The Wall Street Journal*, September 26, 2002, pg. B1.

[2] Dennis Berman, "Behind the Fiber Glut – Innovation Outpaced the Marketplace," *The Wall Street Journal*, September 26, 2002, pg. B1.

optic networks connect major cities using cable laid along railroad, gas pipeline, and other rights of way. This industry segment is not regulated by the FCC or other government agencies, except to the extent that there may be environmental and safety restrictions regarding rights of way. National networks sell high capacity links between specific cities and nationwide coverage to all cities. Their customers are primarily long-distance telephone companies, Internet backbone providers, and large corporations. Many of the companies are vertically integrated into some of these downstream segments. The most famous example is AT&T which also offers long distance telephone service; other firms like Level 3 offer their own Internet backbones.[3] For this paper, we are focusing on the most basic level only – the physical infrastructure that allows these networks to operate. These firms have additional interest because many of them were involved in scandals, including Worldcom, Global Crossing, Qwest, and Enron.

There are several complementary types of infrastructure that we do not study here. These include regional and metropolitan fiber-optic networks and local access networks such as telephone and cable television. Most of the traffic on the national networks has to traverse these other networks as well, but they operate in distinct markets. It is not practical to provide national service by combinations of regional networks, nor is it practical to provide more than very limited regional service on a portion of a national network. While all types of networks experienced major investment in the late 1990s, it was the national fiber-optic networks that appeared to be the most "overbuilt" and were most implicated in the collapse.

To our knowledge there is no economics literature analyzing the national networks' growth and decline. Indeed, very little data has been collected on which firms entered when and where. Until 1998, Jonathan Kraushaar of the Federal Communications Commission published a yearly update on long distance fiber optic networks, but this was discontinued just as industry investment took off. In this paper we present newly collected data that merges Kraushaar's work with publicly available information on firms' entry decisions up to the end of 2001.

Section 2 discusses the relevant theory of firm entry, investment, and sunk costs and applies it to the national fiber-optic network industry. We also compare today's telecoms crisis to the problems of late nineteenth century railroads. In section 3, we describe our data sources and methods of data

[3] Economides (2004) analyzes the Internet backbones and describes how the competition in national fiber networks has made entry quite easy in the backbone market.

collection. We analyze the pattern of entry and the decrease in industry concentration in section 4. In section 5, we test for strategic behavior. Section 6 concludes.

2 Sunk Costs and National Fiber-Optic Networks

The building of the national fiber optic networks is another chapter in the peculiar history of U.S. infrastructure industries. This history started with the canal boom of the early nineteenth century, reached its most dramatic episode in the railroad booms and busts of the late nineteenth century, and has continued since then with electricity transmission, trucking and Interstate highways, and cable television among others. All of these industries have been politically as well as economically important, and all have been characterized by financial instability and/or heavy government regulation.

In particular, the recent telecom boom and bust has been compared to the nineteenth century railroad experience, and the two do appear similar in many regards. In both cases, a large number of firms gained access to rights-of-way between major cities, built multiple parallel routes, and then engaged in intense competition that left many of them bankrupt. But we discuss below that the key to this comparison is the nature of sunk costs in the two industries, and that in fact the two are quite different in this regard.

Entry decisions in high-sunk-cost industries can be represented using a two-stage game (Sutton 1998). In stage 1, firms make irreversible investments that determine their characteristics, such as product variety or quality or some measure of capacity. These investments are industry-specific sunk costs, so the firms do not exit the market later in the game. In stage 2, the firms compete according to Cournot, differentiated Bertrand, or some other type of competition. The terms of this competition are affected by the stage 1 decisions. Sutton suggests that a very loose requirement for a solution to this game is a criterion of viability. That is, firms will not make stage 1 investments that they cannot recoup as operating profit in stage 2.

Faulhaber and Hogendorn (2000) argue that for infrastructure industries like telecom networks, the basic game structure can be further refined as follows: In stage 1, firms invest in *distribution capacity* that determines where they can offer service in geographical space. Then stage 2 can be divided into two parts. In stage 2a, firms invest in *production capacity* that determines how much they can produce in each area that they serve, and in stage 2b they compete in each area subject to these production capacity constraints. The key to this interpretation is that distribution capacity is a sunk cost because investments like rights-of-way, conduits, and utility poles have no alternative use and are not fungible. But production capacity is not sunk because investments like locomotives, telephone switches, and transformers can be resold or redeployed and are therefore fungible.

Under this interpretation, the key to competition between infrastructure firms is geography, since the sunk distribution capacity means that once a firm enters a territory it can commit not to leave. Production capacity, on the other hand, may affect short-run competitive outcomes (for example, it might lead to Cournot outcomes in the manner of Kreps and Scheinkman (1983)), but it does not carry long-run commitment value. For example, entry by a second railroad between two cities would irrevocably increase the number of competitors to two, but it would not inevitably lead to zero-profit Bertrand competition since production capacity (e.g. the number of locomotives) could be adjusted periodically.

For long-haul fiber optic networks, distribution capacity involves securing a right of way, burying protective conduits in this right-of-way, building "huts" to house equipment at intervals along the route, and placing fiber-optic cable inside the conduit.[4] Each strand of fiber has very large data capacity, each cable contains many strands of fiber, and many firms own multiple conduits, so for the foreseeable future no further upgrades to this distribution capacity are necessary.[5]

It is prohibitively expensive to acquire new rights-of-way, so the networks generally follow highways, railroads, and natural gas pipelines. In fact, several of the major networks are associated with companies that own these rights-of-way. Williams, for example, is a natural gas pipeline owner, while Qwest was originally a division of the Southern Pacific Railroad. There is some irony in the comparison with nineteenth century railroads because in many cases the same rights of way were used during the fiber boom.[6]

Production capacity consists of terminal equipment that takes electronic data from many sources,

[4]Planning of these networks is described and modeled in Lanning et al. (2000).

[5]There are periodically advances in the quality of fiber-optic strands, so systems in which it is easier to install new fiber have an advantage in the long run.

[6]The geographic distribution of Internet infrastructure is discussed in Greenstein (forthcoming).

switches and combines it into channels, and converts it to optical signals using lasers. This is called "lighting" the fiber in the industry jargon. Such equipment is expensive but can be moved, resold, expanded, and contracted given sufficient lead time. There are some sunk costs involved, so the quantity of lit fiber has some short-run commitment value. But in the long run, overcapacity and low prices on a particular route should lead to redeployment of equipment away from that route – though it may take some time since an aggregate shock to the industry reduces the resale value of all such equipment. For now the marginal cost of production capacity relative to the size of demand is very small and appears to be causing very low prices.

Why did numerous firms invest in distribution capacity when there were signs that operating profits would be low? Part of the answer is that the number of firms that installed production capacity is much larger than the number that installed distribution capacity. The reason this was possible is that owners of rights-of-way were willing to sell indefeasible rights of use (IRUs) by means of which firms could obtain either space in conduits or dark fiber (fiber optic cable with no terminal equipment attached at the ends). Since most networks contain several conduits and many fibers, it is possible to sell IRUs to the same route several times. For example, the predecessors of both Global Crossing and Genuity obtained IRUs to most of the route miles in Qwest's network in 1997 and 1998.

IRUs convey many of the rights of ownership, but they are typically limited to 20 years, can be dissolved by mutual agreement, and are frequently abrogated by bankruptcy courts. Furthermore, despite the careful language of IRU agreements, in an industry with rapidly changing technology there are likely to be many noncontractables that could render an IRU economically obsolete earlier than its legal expiration.

The fact that so many fiber-optic networks are based on IRUs means that sunk distribution capacity is much less than the number of national networks would suggest. Firms that go bankrupt and hold IRUs are likely to exit the industry once and for all. Only those firms that actually hold right of way are committed to continuing employment of their assets even in the face of bankruptcy reorganization.

Contrast this situation to the nineteenth century railroad boom. Arthur Hadley (1885) discussed how the sunk-cost nature of railroad right of way created perpetual instability in the railroad industry. When competition on a route (New York to Chicago was particularly competitive) was too great to support all the lines on the route, some railroads went bankrupt. But their sunk investment in right of way had no alternative use, so the insolvent line simply emerged from bankruptcy with its debt reduced, and the number of competitors remained the same. This pattern, and the companies' collusive attempts to combat it, eventually led to regulation of the industry.[7]

3 Data

The simplest summary measure of distribution capacity is total route-miles of network.[8] All networks in the sample reach all major American cities, so a network with more route miles serves more small cities and/or has more redundant routes between major cities. The number of route miles thus provides a measure of the effective number of firms competing to provide national service. For example, two 15,000 route mile networks would indicate a symmetric duopoly on service between major cities. In contrast, one 10,000 mile network and one 30,000 mile network would indicate duopoly between major cities but monopoly on subsidiary routes; in this case the overall market would be on average somewhat less competitive. (Clearly the second market would provide more producer plus consumer surplus since it serves more city-pairs, but our interest here is simply that industry profits would be higher in the second case under any plausible oligopolistic form of competition.)

Our data use network route miles to measure the effective number of firms and the quantity of sunk investments. We differentiate between *owned miles* which reflect actual sunk investments in right of way and structures versus *shared miles* which merely reflect investment in IRUs and similar agreements. The sum of these, *total miles,* gives a measure of short-run industry concentration, while owned miles alone gives an upper limit on concentration if all IRUs were dissolved.

In nearly all cases, the promotional and technical materials made available by telecom firms do not

[7] Railroads had, and in large part continue to have, difficulty in sharing trackage because there are extensive economies of scope between train operation and track maintenance (Pittman 2005); these are not present in fiber optic networks.

[8] Each route mile typically contains many strands of fiber-optic cable, so measures of "fiber miles" or "strand miles" are usually many times larger than route miles.

differentiate between the two types of route miles. Thus we reconstructed the process by which each network was built, noting which routes are based on IRUs and which on owned right of way. In some cases, routes are jointly owned, in which case we count one-half the miles for each of two owners and one-third for each of three. Jointly owned routes are a much smaller portion of total mileage than are IRUs and do not greatly affect the totals.

During the period 1986-1998, the FCC collected similar data from the inter-exchange (long distance) telephone companies. These data were compiled and analyzed by Jonathan Kraushaar in what was then the Commission's Common Carrier Bureau, and the reports continue to be available at the FCC's website. The FCC data collection proceeded through voluntary questionnaires and telephone calls, and they received a high response rate. Toward the end of the sample period, they expressed concern that fiber routes miles were being double-counted, precisely for the reasons we discussed above. We use the FCC data for nearly all firms that had fiber networks during the period 1990-96, with some corrections for shared mileage. For 1997-98, we use the FCC data primarily as a check against our own data. From 1999-2001 we must rely on our own data exclusively. We found that in most cases our data was consistent with the FCC's.

Our main source for total route miles is the firms' annual reports and investment prospectuses as filed with the Securities and Exchange Commission and available through the online EDGAR database (primarily forms 10-K and S-4). Some companies included very meticulous network data with these filings, while others simply mentioned route miles in passing.

To supplement that source, we also searched each company's press releases using the archives on LEXIS/NEXIS. In many cases, firms obtained routes by swapping IRUs to their own right of way for IRUs to the right of way of their competitors. The firms often announced and promoted these swaps as an inexpensive way to build their network quickly. In several cases, firms swapped access to a preexisting IRU for a preexisting IRU on another firm's route, so that the swaps could be more than one layer deep. Because of this, we frequently know that a route is based on an IRU but cannot definitely determine the source of that IRU. Fortunately, this problem does not affect the computation of owned versus shared route miles.

The firms' reports were checked on a route-by-route basis against network maps available at the companies' web sites (in most cases) or from Internet service provider resellers (for Qwest, MCI-

Worldcom, McLeodUSA, and ENRON). They were also checked against the map "North American National and Regional Fiberoptic Long-Haul Routes Planned and In Place" published by KMI Research and dated May 2002. The inconsistencies were minor.

Although we are quite confident that the routes identified as shared are in fact shared, there are probably additional IRUs and swaps that were not reported. As such, the database is conservative since it attributes all other miles as owned. We were not able to find as complete data on Sprint as on other networks. All our sources suggest that Sprint's network was largely completed before the sample period and not significantly expanded thereafter. For years in which no data was available for Sprint, we have assumed no expansion and entered the previous year's figure.

The sample is limited to firms that either achieved national reach or had announced aspirations to national reach. Regional networks (which include the local telephone companies) are not counted. They actually include the majority of fiber in the United States, but they do not compete in the same national market. Providing national coverage by piecing together circuits from regional networks is too expensive and unreliable to be competitive.[9] We also exclude firms that purchased access to national networks but did not own any mileage of their own and did not participate in any swaps of IRUs; these were customers, not peers, of the carriers listed.

4 Entry and Investment

We now document the pattern of entry and show that a large proportion of investment is shared miles. When only owned miles are considered, entry appears more moderate and industry concentration more typical of a high-sunk-cost industry.

Table 1 shows total network route miles (owned plus shared) by firm for the period 1990-2001. We

[9] The excluded regional networks are the Regional Bell Operating Companies (RBOCs) and Alltel, Black Hills Fibercom, C3 Networks, Columbia Transcom, Connectiv, Dominion Telecom, Dukenet, El Paso Global Networks, Electric Lightwave, Entergy, Florida Fiber Network, FPL Fibernet, GPU Telecom, Iowa Network Services, ITC Deltacom, Kentucky Data Link, Logix Communications, MP Telecom, NEON, Norlight, Onvoy, Palmetonet, Progress Telecom, SON Communications, Telergy, Time Warner Telecom, and Valleynet. Several of the firms that are included are essentially regional carriers that expanded to national reach through IRUs. These are DTI, EPIK, Metromedia, Pathnet, and Touch America.

include both "lit" and "dark" miles since the dark miles would still be expected to exert competitive pressures in the long run. During the early 1990s, three large long distance companies, AT&T, MCI, and Sprint, had been joined by Williams, a natural gas pipeline company that built a nationwide fiber optic network. Williams sold this network to Worldcom in 1995.[10]

In 1997 – two years after the Netscape initial public offering launched the Internet as a major commercial force and one year after passage of the Telecommunications Act – growth in route miles increased rapidly. This was a combination of expansion by existing networks and *de novo* entry. By 2001, there were 19 national networks, but profits were low and Pathnet had exited the market, while EPIK contracted back to its Florida base. In 2002, almost all of these firms were in bankruptcy.

EPIK's sudden contraction from national to regional network demonstrates that the distribution capacity of some of these companies did not consist of sunk assets. Tables 2 and 3 show route miles actually owned by each firm in each of the years and the percentage of total route miles that were owned. At the beginning of the 1990s, all networks were owned outright by the carriers. But entry in the later 90s involved so many swaps and IRUs that many "national" carriers owned only a small percent of their rights of way, and in a few cases owned none at all.

The bulk of total investment in network route miles came during 1998, 1999, and 2000. The majority of the new miles in this period were shared. New right of way built in this period is mostly accounted for by upgrades to the old AT&T and MCIWorldcom networks and the entry of three new major networks, Qwest, Level 3, and Williams (see Figure 1). One way to interpret this is that four incumbents were joined by three entrants and fringe firms that were partially dependent on the seven major networks.

These data suggest that the industry did not experience overbuilding and ruinous competition along the same lines as the railroads of the late 1800s. Rather, actual construction of new rights of way represented modest entry, but the swaps of IRUs created a very competitive environment in which prices fell.

[10] The FCC's Worldcom data appears to include regional networks. We use only national route miles reported by Worldcom (and its predecessor LDDS) in SEC filings.

The Herfindahl-Hirschman Indices (HHIs) and the equivalent number of equal-sized firms (calculated from the inverse of the HHI) for each year based on total miles and owned miles appear in Table 4. Not all of the networks use their capacity equally, but these measures based on route miles do provide a guide to the potential long-run industry structure.

The difference between competition in terms of total miles and owned miles is striking. Using total miles, the industry moved from an oligopolistic HHI to a very competitive one. But using owned miles, the industry remained above the 1,000 limit for government scrutiny of mergers based on the Department of Justice's *1992 Horizontal Merger Guidelines*. Still, there were eight equivalent equal-sized firms using owned miles, which is a large number of competitors by the standards of previous infrastructure developments such as railroads and early telephone.

We have now shown that shared miles made up a very substantial portion of entry into the industry. Total miles grew so fast as to push concentration measures into an unsupportable region. But using owned miles, entry was more measured and concentration remained in the oligopoly range. By these measures, we conclude that while total miles may not have been viable, owned miles were probably much closer to viability (if they had not been shared out). Why would firms invest in miles that were not viable? One answer is that there was a race to capture a leading position in the industry, and the investment was strategic. In the next section, we test this hypothesis.

5 Testing for Strategic Behavior

Instability and overcapacity in infrastructure industries are frequently attributed to strategic behavior connected with sunk costs. Many dynamic models of firm investment show that a firm moving earlier should invest more than the static optimum in order to reduce the extent of investment by later entrants (e.g. Dixit (1980), Fudenberg and Tirole (1983)). We will call this behavior *building ahead* to avoid the pejorative tone of specific examples of this behavior like entry deterrence, preemption, or "top dog." Typically building ahead only works if the initial investment is sunk and therefore involves a long-term commitment, thus, it can work particularly well in infrastructure industries. If building ahead occurs, and there is an unanticipated shock that suddenly stops investment, then the industry's excess capacity will be particularly large.

Our alternative hypothesis to building ahead is "symmetric investment." Suppose a group of firms (possibly including new entrants) is subject to a favorable demand or technology shock and invests to take advantage of the opportunity. If each firm believes that its investment *timing* will have a negligible influence on the other firms' eventual *cumulative* investment, then there is no reason to invest beyond the static optimum. As the opportunity grows, all such firms will invest at rates that are not influenced by the prior investment of other firms. Under symmetric investment, an unanticipated negative shock will still lead to excess capacity, but it will be less than under building ahead and will not be attributable to market failure resulting from strategic excesses.

In this section we analyze the data to test whether networks were built ahead or experienced symmetric investment. Our method is based on Gilbert and Lieberman (1987) (hereafter GL). GL examine capacity data in the chemical industry to determine whether it is consistent with a model of "preemption" (building ahead) or "maintaing market share" (symmetric investment).

GL collect data on 24 chemical products produced by 3 to 20 firms, circa 1960 through 1982. The dependent variable is binary: $y_{i,j,t} = 1$ if firm i increased its capacity to produce product j in year t by more than 5%. The 5% threshold is arbitrary, but they claim that using other thresholds does not affect the results. The reason to use a binary variable is to avoid scaling problems since small firms have huge percent changes in their early years. All observations begin two years after the firm enters the industry, so the startup capacity investment is excluded.

GL's independent variables are constructed from firm i's production capacity and the total industry output. They are: capacity utilization (averaged over two years), growth rate of output (averaged over four years), the firm's share of total capacity, the change in the firm's capacity share (over a two year period), and a "bandwagon effect" that measures the percent increase in all rivals' capacity. Because they expect that large and small firms may behave differently, they interact all the variables with the firm's capacity share.

They argue that the coefficients on these variables provide a test for strategic investment. If firms build ahead, then investment will not be affected by capacity share since other considerations will drive firm behavior. Instead it will respond negatively to bandwagon investment (since that implies that rivals have already built ahead) and positively to capacity utilization (since building ahead implies an effort to keep capacity high relative to revenue).

Suppose that instead of building ahead, there is a symmetric capacity expansion. The probability of a firm investing aggressively may not be affected by capacity utilization, but it responds negatively to changes in capacity share since firms will roughly maintain their market shares. Investment should respond positively to bandwagon investment by others since firms have to keep up with one another in order to maintain their positions in the industry.

GL's estimates show small chemical firms, below 9% market share, build ahead while large firms seem to maintain market share. To bolster this result, they estimate a restricted model with only the variables expected to affect building ahead. The reduced model is rejected on the basis of a likelihood ratio test in favor of the full model. Its estimates again suggest that large firms can be deterred.

We apply this model to our data on the fiber optic industry. The company reports frequently give plans to put new route miles in service within one year, so we convert all lags to one year. We face three main difficulties in translating GL's model, namely what constitutes capacity, output, and capacity utilization.

For a measure of capacity we use route miles. As we have argued above, all of the networks are similar in terms of coverage of the entire country, so additional route miles imply a more dense, more robust network. The actual production capacity of each link in the network is not important because the advances in fiber optic technology essentially eliminated data throughput constraints. Thus mileage, and the associated density of the network, is the key capacity decision. We label firm i's total and owned miles in year t by $M_{i,t}^T$ and $M_{i,t}^O$ respectively.

We cannot directly observe the output of these communications networks; such data are difficult to measure even for the owners of the networks themselves and are not publicly available. Instead we proxy for industry output with industry revenue. Revenues of the long distance networks themselves are the seemingly logical focus of interest, but there are two problems with using them. First, many of the firms, such as AT&T, derive most of their revenue from lines of business not directly related to their long-haul networks. The firms do not report sufficiently disaggregated revenue to correct for this problem. Second, the networks' revenue is determined endogenously with investment in route miles, so proper estimation would require good instruments. As an alternative, we use total revenue of the U.S. telecoms industry. Since these data include various local telephone, wireless telephone, and business services, they should remove much of the endogeneity problem and provide an index for opportunities to build additional route miles. The source for these data is the International Telecommunications Union *Yearbook of Statistics*, 2003 and 2000 editions. Yearly revenue (REV_t) and growth in revenue ($GROW_t = (REV_t/REV_{t-1}) - 1$) are reported in Table 5.[11] Revenue is measured in 1995 dollars using the consumer price index.

Finally, we need a measure of capacity utilization. The same problems with output data occur here too, so we compare growth in revenue to growth in capacity. We calculate a Revenue per Mile Index for both total and owned miles, RMI_t^T and RMI_t^O, by comparing revenue per mile in year t with revenue per mile in 1990. Thus, if firm i's total and owned miles in year t are $M_{i,t}^T$ and $M_{i,t}^O$,

$$RMI_t^j = \frac{\frac{REV_t}{\sum_i M_{i,t}^j}}{\frac{REV_{1990}}{\sum_i M_{i,1990}^j}} \quad j = T, O$$

In 1990 there appear to have been modest opportunities to expand route miles since there was a gradual increase in miles in the succeeding years. Relative to this base level, $RMI > 1$ indicates relatively better opportunities while $RMI < 1$ indicates relatively poorer ones.

An interesting feature of these data is that in 1995-97, there were arguably opportunities to add route mileage (based on revenue), particularly when looking at owned miles only. By the end of the sample period, revenue per mile had fallen sharply. Owned miles show much less of this trend than total miles due to the extensive use of shared mileage.

Given these interpretations of capacity, output, and capacity utilization, we can construct the rest of GL's independent variables as follows. Firm i's share of total industry mileage in year t is

$$SHARE_{i,t}^j = \frac{M_{i,t}^j}{\sum_i M_{i,t}^j} \quad j = T, O$$

The change in that share from year $t-1$ to year t is

$$DELSHARE_{i,t}^j = \frac{SHARE_{i,t}^j}{SHARE_{i,t-1}^j} \quad j = T, O$$

The "bandwagon effect" that measures investment by firm i's competitors during year t is

$$BAND_{i,t}^j = \frac{\sum_{k \neq i}(M_{k,t}^j - M_{k,t-1}^j)}{\sum_{k \neq i} M_{k,t-1}^j} \quad j = T, O$$

[11] An alternative growth measure, Internet traffic growth, proved to be highly collinear.

Note that the bandwagon variable is different from *DELSHARE* because it concerns investment in the current year and it does not account for a firm's own investment. The correlation between *BAND* and *DELSHARE* is $R = 0.10$ for total miles and $R = 0.14$ for owned miles.

Because small firms may differ from large firms, all variables are interacted with *SHARE*. Since investment decisions must be taken prior to their realizations, all variables are lagged one year except for *BAND*.

The dependent variable is binary and measures whether route miles were increased substantially in a given year. For some threshold change d, define

$$Y_{i,t}^{j} = 1 \quad \text{if} \quad \frac{M_{i,t}^{j} - M_{i,t-1}^{j}}{M_{i,t-1}^{j}} > d \quad j = T, O$$

and 0 otherwise. The reason to use the binary variable is that smaller firms have huge percentage additions in some years, which introduces scaling problems. We want to choose d to represent firms that made significant investments over and above the general trend in the industry. We remove the first year for new entrants from the sample. Then we observe the median and 40th, 60th, and 70th percentile growth in route miles across all observations (see Table 6). We run several regressions, defining the dependent variable using d equal to each of these percentile values.

The results of probit analysis using total miles are reported in Table 7, along with the predicted signs under the two hypotheses. The different cutoff levels d seem to affect significance levels more than magnitudes of the estimates. Changes in market share clearly do not affect investment, which is characteristic of building ahead. The bandwagon effect is positive for small firms but negative for larger ones (though only significant for the median case). This may suggest that small firms were building ahead and reducing investment by large ones. For the median case ($d = 7.3\%$), the boundary between "large" and "small" firms is 10.8% capacity share, roughly the size of the four major incumbents.[12]

Following GL, we also ran regressions omitting the variables *SHARE* and *DELSHARE* since they are not expected to affect building ahead. The signs of the estimates do not change on the remaining variables. Likelihood ratio tests accept the building ahead model for the 40th, 50th, and 60th

[12]GL warn that favorable shocks to investment payoffs could make the bandwagon effect positive even under the building ahead hypothesis. That may have occurred here, in which case our evidence does not rule out the small firms building ahead of one another.

percentile cases, and reject for the 70th percentile case.[13] This suggests that building ahead, at least by small firms, is a plausible explanation for investment in total miles.

Table 8 reports results using owned miles only. The sample is slightly smaller because in four cases firms entered the market with zero owned miles in their first year. In many respects, the results are similar to total miles. Again the coefficients on *BAND* suggest that smaller firms may have built ahead of larger ones, with the boundary between firm sizes at about 13% capacity share. However, the *DELSHARE* variables are now significant also, which is not expected in GL.

The restricted model fits more poorly for owned miles than for total miles. For all but the 70th percentile case, it is rejected by likelihood ratio test.[14] No doubt this is because of the greater importance of the *DELSHARE* variables. Thus, the evidence for building ahead is much more limited and more mixed than in the total miles case.

We believe that two conclusions can be gleaned from these results:

First, and most important, the carriers that were building owned miles and incurring sunk costs do not appear to have been building ahead to reduce rivals' investment. (Or if they tried this strategy, it generally failed.) Strategic overbuilding is often mentioned as a weakness of unregulated infrastructure industries, but the basic installation of the the fiber optic networks does not follow this pattern.

Second, there is some evidence for strategic building ahead of total miles. Again this points to IRUs as being a destabilizing factor in the industry since they appear to have been used to deter other investments. In particular, several smaller firms entered the market using IRUs and this seems to have resulted in the larger firms backing off on investment.

This second point is somewhat paradoxical when we consider that IRUs are not too sunk, and therefore are not the best way to carry out a building ahead strategy. Probably the most plausible interpretation is that IRUs served as a sort of "placeholder" or even a form of (fairly) cheap talk to coordinate which firms would build national networks. Once the market was filled up by firms using IRUs, the incumbent firms had less incentive to invest. Building ahead is essentially a speculative

[13] p-values of 46%, 81%, 37% and 4% respectively.

[14] p-values of 0.3%, 0.6%, 1.1%, and 25.9% respectively.

strategy, and it appears that IRUs' lower cost trumped their lower commitment value for firms following that strategy.

6 Conclusion

We have examined the number of fiber-optic route miles built by U.S. telecom firms from 1990-2001. By sorting through each firm's SEC reports and press releases, we have been able to discover which routes are based on sunk investments in right of way and conduit and which are based on relatively non-sunk investment in IRUs. We find that more than half of total route miles added during this period were based on non-sunk forms of investment. We conclude that the loss-producing level of competition that has prevailed since 2001 is due more to the willingness of firms to sell IRUs than to actual over-investment like that which occurred in the nineteenth century railroad boom.

We calculated a Revenue per Mile Index based on industry-wide changes in revenue per route mile from a 1990 base. This measure suggests that there were opportunities for increased investment in route miles in the mid 1990s, but that investment after that proceeded much faster than revenue growth. Using Gilbert and Lieberman's (1987) model of oligopoly investment, we find some evidence of firms building ahead of others with regard to total miles; this could lead to excessive entry from an *ex post* perspective. Applying the same analysis to owned miles produces less evidence of building ahead.

Our general conclusion is that the only "excessive" element of national fiber optic network investment was the very extensive sharing of route miles using IRUs. Some of this sharing may have involved strategic behavior, and it led to remarkably low concentration for an industry with such high fixed, sunk costs. Not including this sharing, the underlying investment in owned route miles was more moderate, led to fairly reasonable concentration, and does not appear to have involved speculative strategies.

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Figures and Tables

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
360 Networks (Worldwide Fiber)									1,181	7,971	11,976	14,176
AT&T	32,398	32,500	33,500	35,000	36,022	37,419	38,704	38,704	39,576	39,576	42,551	46,500
Broadwing (IXC)	914	914	914	1,257	1,357	1,365	2,025	5,500	9,300	15,700	18,500	18,500
DTI								927	1,500	7,250	14,360	17,835
Dynegy												16,000
ENRON									3,400	16,281	16,281	16,281
EPIK (Florida East Coast RR)										3,801	11,500	1,244
Genuity (GTE)								5,283	12,000	17,500	17,500	20,800
Global Crossing (Frontier)								4,932	9,620	13,000	20,000	20,000
Level 3									410	9,084	15,236	15,639
MCI	16,000	16,700	17,040	19,793	21,460	21,049	23,096	25,234				
McLeodUSA (+CapRock)	332	332	332	332	519	519	621	866	5,052	8,036	16,600	26,000
Metromedia									3,099	18,000	18,000	18,000
Pathnet										478	1,500	
Qwest (Southern Pacific RR, +LCI)	1,210	1,406	1,406	1,406	1,408	1,408	3,977	7,101	15,000	25,500	25,500	23,700
Sprint (limited data)	22,093	22,725	22,799	22,996	22,996	22,996	23,432	23,574	23,574	23,574	23,574	23,574
Touch America (Montana Power)								2,770	9,770	10,466	17,370	21,370
Velocita (PF.net)												4,000
Williams	9,700	9,700	9,700	9,700	9,700	0	0	0	9,300	17,000	20,800	28,700
Worldcom/MCIWorldcom (LDDS)					1,300	11,000	12,589	19,619	47,529	47,806	47,806	47,806
XO (NEXTLINK)											16,000	16,000
Total	82,647	84,277	85,691	90,484	94,762	95,756	104,444	134,510	190,311	281,023	355,054	396,125
% change		2.0%	1.7%	5.6%	4.7%	1.0%	9.1%	28.8%	41.5%	47.7%	26.3%	11.6%

Table 1: Total Route Miles, 1990-2001

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
360 Networks (Worldwide Fiber)									1,181	3,709	5,309	6,764
AT&T	32,398	32,500	33,500	35,000	36,022	37,419	38,704	38,704	39,576	39,576	41,064	44,009
Broadwing (IXC)	914	914	914	1,257	1,357	1,365	2,025	4,647	6,028	11,186	12,666	12,666
DTI								927	1,500	1,900	4,650	4,900
Dynegy												0
ENRON									1,740	1,740	1,740	1,740
EPIK (Florida East Coast RR)										790	894	1,244
Genuity (GTE)								0	0	2,753	2,753	6,053
Global Crossing (Frontier)								0	0	0	0	0
Level 3									410	9,022	15,174	15,577
MCI	16,000	16,700	17,040	16,793	18,207	17,858	19,595	25,234				
McLeodUSA (+CapRock)	332	332	332	332	519	519	621	866	5,052	8,036	9,475	9,740
Metromedia									0	255	255	255
Pathnet										239	980	
Qwest (Southern Pacific RR, +LCI)	1,210	1,406	1,406	1,406	1,408	1,408	3,977	7,101	14,467	16,322	16,322	14,522
Sprint (limited data)	22,093	22,725	22,799	22,996	22,996	22,996	23,432	23,574	23,574	23,574	23,574	23,574
Touch America (Montana Power)								137	3,263	3,308	7,820	8,147
Velocita (PF.net)												1,462
Williams	9,700	9,700	9,700	9,700	9,700	0	0	0	1,830	10,101	14,812	17,800
Worldcom/MCIWorldcom (LDDS)					1,300	11,000	12,589	13,878	41,788	42,065	42,065	42,065
XO (NEXTLINK)											0	0
Total	82,647	84,277	85,691	87,484	91,509	92,565	100,943	115,068	140,409	174,575	199,551	210,516
% change		2.0%	1.7%	2.1%	4.6%	1.2%	9.1%	14.0%	22.0%	24.3%	14.3%	5.5%

Table 2: Owned Route Miles, 1990-2001

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
360 Networks (Worldwide Fiber)									100%	47%	44%	48%
AT&T	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	97%	95%
Broadwing (IXC)	100%	100%	100%	100%	100%	100%	100%	84%	65%	71%	68%	68%
DTI								100%	100%	26%	32%	27%
Dynegy												0%
ENRON									51%	11%	11%	11%
EPIK (Florida East Coast RR)										21%	8%	100%
Genuity (GTE)								0%	0%	16%	16%	29%
Global Crossing (Frontier)								0%	0%	0%	0%	0%
Level 3									100%	99%	100%	100%
MCI	100%	100%	100%	85%	85%	85%	85%	100%				
McLeodUSA (+CapRock)	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	57%	37%
Metromedia									0%	1%	1%	1%
Pathnet										50%	65%	
Qwest (Southern Pacific RR, +LCI)	100%	100%	100%	100%	100%	100%	100%	100%	96%	64%	64%	61%
Sprint (limited data)	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Touch America (Montana Power)								5%	33%	32%	45%	38%
Velocita (PF.net)												37%
Williams	100%	100%	100%	100%	100%				20%	59%	71%	62%
Worldcom/MCIWorldcom (LDDS)					100%	100%	100%	71%	88%	88%	88%	88%
XO (NEXTLINK)											0%	0%
Total	100%	100%	100%	97%	97%	97%	97%	86%	74%	62%	56%	53%

Table 3: Percentage of Total Route Miles Owned, 1990-2001

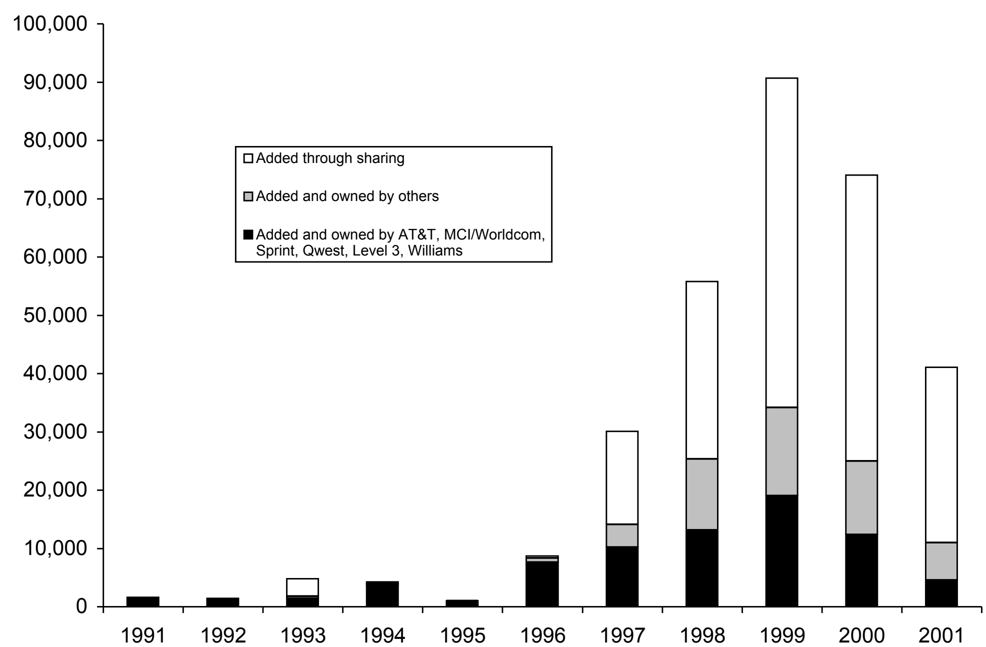

Figure 1: Yearly Additions to Total Route Miles, 1990-2001

Year	HHI Total Miles	HHI Owned Miles	Equal-Sized Firms Total Miles	Equal-Sized Firms Owned Miles
1990	2,767	2,767	3.6	3.6
1991	2,743	2,743	3.6	3.6
1992	2,764	2,764	3.6	3.6
1993	2,740	2,788	3.6	3.6
1994	2,658	2,696	3.8	3.7
1995	2,723	2,770	3.7	3.6
1996	2,529	2,561	4.0	3.9
1997	1,778	2,233	5.6	4.5
1998	1,425	2,110	7.0	4.7
1999	892	1,500	11.2	6.7
2000	708	1,281	14.1	7.8
2001	674	1,234	14.8	8.1

Table 4: HHIs and Equivalent Number of Firms, 1990-2001

Year	REV	$GROW$	RMI^T	RMI^O
1990	155.8	-2.4%	1.00	1.00
1991	155.1	-0.5%	0.98	0.98
1992	159.8	3.0%	0.99	0.99
1993	163.2	2.1%	0.96	0.99
1994	170.1	4.3%	0.95	0.99
1995	175.0	2.9%	0.97	1.00
1996	205.8	17.6%	1.05	1.08
1997	220.0	6.9%	0.87	1.01
1998	229.9	4.5%	0.64	0.87
1999	246.8	7.3%	0.47	0.75
2000	259.3	5.1%	0.39	0.69
2001	261.2	0.7%	0.35	0.66

Table 5: Revenue and Revenue per Mile Index, 1990-2001
(Revenue in billions of 1995 dollars)

Percentile	Total Miles	Owned Miles
40	2.0%	0.7%
50	7.3%	3.3%
60	18.6%	9.2%
70	48.9%	24.7%

Table 6: Percent Change in Total and Owned Miles
(Not including first year for new entrants)

Variable	(BA/SI)	$d = 2.0\%$	$d = 7.3\%$	$d = 18.6\%$	$d = 48.9\%$
$SHARE^T_{t-1}$		-19.5	-2.7	-38.1	-81.1**
		0.16	0.86	0.34	0.05
RMI^T_{t-1}	(+/0)	-0.4	1.5	-0.5	-2.8
		0.72	0.28	0.81	0.16
$RMI^T_{t-1} \times SHARE^T_{t-1}$		24.4*	-0.4	42.2	81.9**
		0.07	0.98	0.25	0.04
$GROW_{t-1}$		18.3	25.1*	33.8**	7.5
		0.15	0.10	0.05	0.31
$GROW_{t-1} \times SHARE^T_{t-1}$		-98.6	-40.3	-157.4	-51.5
		0.13	0.63	0.22	0.60
$DELSHARE^T_{t-1}$	(0/−)	0.0	-0.1	0.2	0.2
		0.99	0.68	0.64	0.55
$DELSHARE^T_{t-1} \times SHARE^T_{t-1}$		1.1	2.3	-6.9	-2.8
		0.72	0.44	0.56	0.66
$BAND^T_t$	(−/+)	4.0**	5.0**	5.2**	5.0**
		0.02	0.01	0.05	0.02
$BAND^T_t \times SHARE^T_{t-1}$		-14.0	-46.3**	-22.7	-10.4
		0.21	0.05	0.57	0.78
constant		-0.5	-2.2	-1.0	1.4
		0.70	0.16	0.67	0.48
N		101	101	101	101
Log Likelihood		-51.3	-45.6	-32.2	-31.5

Table 7: Probit Analysis of Expansion in Total Miles
(BA/SI) = predicted signs, Building Ahead/Simultaneous Investment hypotheses
p-values below estimates.
** Significant at 0.05 level.
* Significant at 0.10 level.

Variable	(BA/SI)	$d = 0.7\%$	$d = 3.3\%$	$d = 9.2\%$	$d = 24.7\%$
$SHARE^O_{t-1}$		17.1	22.2	14.4	44.1
		0.26	0.16	0.42	0.11
RMI^O_{t-1}	(+/0)	2.1	3.2	4.0*	7.3**
		0.29	0.11	0.06	0.01
$RMI^O_{t-1} \times SHARE^O_{t-1}$		2.3	-14.6	-31.4*	-50.7*
		0.87	0.32	0.09	0.08
$GROW_{t-1}$		18.4	16.5	22.2	36.1**
		0.14	0.20	0.12	0.03
$GROW_{t-1} \times SHARE^O_{t-1}$		-91.0	-36.5	-15.0	-133.4
		0.14	0.56	0.86	0.26
$DELSHARE^O_{t-1}$	$(0/-)$	3.3**	2.2**	-0.5**	-0.1
		0.01	0.04	0.02	0.20
$DELSHARE^O_{t-1} \times SHARE^O_{t-1}$		-12.4*	-5.0	14.8**	2.3
		0.06	0.47	0.05	0.25
$BAND^O_t$	$(-/+)$	6.3**	7.8**	8.8**	9.8**
		0.04	0.02	0.01	0.01
$BAND^O_t \times SHARE^O_{t-1}$		-31.8**	-54.0**	-96.8**	-76.6
		0.04	0.01	0.01	0.16
constant		-6.4**	-6.3**	-4.3**	-8.6**
		0.01	0.01	0.05	0.00
N		97	97	97	97
Log Likelihood		-44.8	-44.2	-38.8	-31.2

Table 8: Probit Analysis of Expansion in Owned Miles
(BA/SI) = predicted signs, Building Ahead/Simultaneous Investment hypotheses
p-values below estimates.
** Significant at 0.05 level.
* Significant at 0.10 level.