Open Access Rules and Equilibrium Broadband Deployment

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Introduction

Investment in advanced communications infrastructure promises such tantalizing payoffs as accelerated economic growth and enhanced national competitiveness. Relatively little disagreement arises in policy debates that such benefits are possible—usually only their size and distribution across the population are at issue. Bitter disputes, however, have broken out over which path will lead the communications sector to deploy these technologies most expeditiously and equitably.

While competition is now widely accepted as essential to effective broadband policy, policy makers have adopted a wide array of alternative rules to promote advanced network investment. Arguably, the most contentious of these policies forces incumbent network owners to share their facilities and equipment to enable rival broadband service providers. Opponents protest that such sharing destroys incentives to undertake the expense and risk of deploying new technologies. Such policies, they contend, will likely delay the rollout of innovative services, and possibly forestall deployment in some markets altogether. Proponents of 'open access,'[1] in contrast, emphasize how sharing creates competition in retail service competition without the waste of duplicate investment. In its strong form, this view foresees future facilities-based competition the results in net increase in advanced network investment.

The impact of pro-competition policy on broadband deployment has generated a considerable body of empirical evidence. This literature predates the opening of many advanced service markets to competition.[2] Several early econometric investigations concluded that liberalized regulation of incumbent telephone companies had the effect of stimulating their investment in advanced technology.[3] The empirical evidence on this question is far less conclusive once those communications markets were open to competition, no doubt partly a result that

[1] We use 'open access' to refer to policies that require facilities-based providers to share their networks with downstream service rivals. In the US, the term has been used to describe nondiscriminatory interconnection between a cable TV system and affiliated and unaffiliated Internet Service Providers (ISPs).

[2] Woroch (1998) provides a review of earlier empirical studies of the competition-investment relationship in telecommunications and other deregulated industries.

[3] In particular, Greenstein et al. (1995) and Kridel et al. (1996) find that price cap regulation (or its variants) is associated with increased investment by local telephone incumbents in new digital technology, including optical fiber.

the studies were conducted on behalf of interested parties. For instance, Willig et al. (2002) conclude that aggregate incumbent local exchange carrier (ILEC) investment is inversely related to unbundled network element prices. Haring et al. (2002) take issue with this conclusion. In comparison, Crandall et al. (2002) offer some impressionistic evidence that leads them to conclude unbundling reduces investment by ILECs. Gabel and Huang (2003) and Floyd and Gabel (2003) estimate simultaneous equations models of ILEC deployment of packet switching and of the presence of competitive local carriers as a function of regulatory treatment and market conditions. They find, contrary to the earlier analysis, that traditional rate of return regulation is associated with a greater propensity to deploy advanced technology.

A longer-run rationale for open access is the possibility that it will facilitate infrastructure competition by providing entrants a ‘stepping stone’ whereby they are able to market some kind of service while they are building their own network. By getting to market more quickly, entrants may be more potent competitors when infrastructure competition materializes. Examining an early period of competition, Woroch (2000) finds evidence that facilities-based entry triggers a virtuous cycle whereby incumbent carriers respond by deploying urban fiber rings as both compete for high-speed business access customers. Addressing a similar question, Crandall, et al. (2002) estimate a relatively high elasticity of substitution between leased and purchased local loops, and conclude that low lease rates significantly discourage facilities-based entry.

In the end, no consensus emerges from the empirical literature examining the impact of regulation-mandated competition and the extent of firm-specific and industry-wide investment. Based on superficial modeling, the empirical studies are incapable of capturing the complex relationship between the pro-competitive policy and incumbents’ and entrants’ investment incentives. Equilibrium investment behavior—especially when it involves innovation—does not obey a simple direct relation to standard measures of competition.[4] Furthermore, broadband policy can be highly idiosyncratic, generating unique, and unexpected, consequences for broadband investment.

The principal contribution of this paper is to provide a formal model that links open access policies with equilibrium deployment of advanced networks which, in turn, generate hypotheses to guide empirical tests and inform broadband policy initiatives. We model the timing of deployment of broadband services as a ‘technology race’ among competing network owners and service providers. In equilibrium, firms decide if and when to deploy broadband technology. Depending on identifiable demand and cost conditions, any contestant may ‘win’ this race. The model with two firms depicts the vigorous contests taking place in nearly all countries between incumbent local telephone companies and cable television operators that are deploying digital subscriber line (DSL) and cable modem (CM) technology, respectively.

Properties of the equilibrium technology race are then used to characterize the impact of various open access policies on the outcome of broadband race.

[4] See Boone (2000).

Regulatory policy affects the outcome of this race by altering participants' investment incentives and, in turn, the pace of deployment and the winning technology. We begin by examining the indirect role of non-broadband regulation on broadband deployment incentives. Rate regulation of traditional services, e.g., voice telephony and broadcast video, will be irrelevant if it is uncoupled from the broadband deployment decision. Legacy regulation could nevertheless further constrain profits due to cost sharing rules and the like. In that case, non-broadband regulation will tend to delay broadband deployment by both carriers even if they are treated symmetrically.

Next we turn to a simple policy of sharing a monopoly incumbent's advanced network and sharing it with a single pure reseller of broadband services. In that case the outcome is unambiguous: a policy of open access delays deployment, and might even preclude it. On balance whether social welfare is reduced depends on the extent to which consumers benefit from lower broadband service prices.

Turning to a setting with two facilities-based contenders, we consider a policy that mandates the leader share its broadband network with its rival while that latter builds its own facilities. Again, both deployment dates are postponed relative to the outcome without sharing. This version of the open access is indicative to asymmetric treatment of local telephone companies and cable TV operators. Mandating that both incumbents must make their broadband facilities available to its rival may reverse this tendency and accelerate deployment. One last open access policy allows a follower to continue to lease the leader's network even after it has built its own network. Allowed to both lease and build broadband facilities, the follower's incentive to upgrade its own network is diminished, delaying the date of platform competition as well as delaying initial construction of broadband network. Similar impacts on deployment arise when regulators mandate pure resale, in which case resellers can lease broadband networks at regulated wholesale rates but with no opportunity to build their own facilities. When pure resellers are ruled out, and both carriers gain access to the other's broadband network, we find that initial deployment will be delayed even when profit regulation is applied symmetrically. In this case, however, it is possible that the order of deployment is reversed, in which case an inferior technology could be deployed before the superior one.

In the next section we describe some distinguishing features of broadband technology that we hope to capture by the technology race model, as well as several of the more prominent forms of broadband regulation. We then construct the technology race model of broadband deployment and briefly describe equilibrium and some comparative statics properties, relegating much of the derivation to an appendix. The subsequent sections are devoted to analyzing the variants of the open access rules. A final section concludes with remarks about a broader welfare issues of facility sharing policies.

Broadband Technology and Regulation

Broadband service is defined chiefly by its bidirectional data transmission speed.[5] Whereas bit rates exceeding 200 kbps were once considered broadband service, much faster thresholds are required for that classification today. In reality transmission speeds vary continuously even for the same technology deployed within a single region. Minimum speeds to meet users' demands will increase further as content and applications become available that take full advantage of the greater bandwidth.

Many kinds of physical networks can deliver high-speed data. The two most common technologies are DSL over the public switched telephone network and cable modem over cable TV systems.[6] The duopoly race that is the focus of much of the analysis below is easily interpreted as competition between an incumbent local telephone company and a cable TV operator. Wireless networks—3G cellular, WiFi, and two-way satellite—represent a smaller, but rapidly growing share of the broadband access market. New wire-based networks are also being built in competition with embedded networks.[7] These broadband service providers sometimes undertake green field construction of fiber networks and at other times retrofit of existing cable TV systems.[8]

Broadband Technology and Cost Characteristics

Technologies for delivering broadband services continue to experience steady improvements, leading to increased speeds and falling costs. Progress of broadband technologies remain highly uncertain, however, as they depend on overcoming many technical challenges and on the shifting capabilities of embedded networks.

The investment needed to deploy broadband service is very lumpy. Although some expenditures vary with the scale of the broadband network,[9] the vast

[5] Other key attributes include an always-on connection and unrestricted access to the Internet. Transmission rates may be further qualified by the constancy of the bitrate and the asymmetry in upload and download speeds.

[6] International Telecommunication Union (ITU, 2003) gives penetration of the leading broadband tcchnologies among select developed countries.

[7] The electricity grid represents an existing wireline network that potentially can carry broadband services using Powerline transmission technology.

[8] See GAO (2004) for six case studies of such broadband deployments in the U.S.

[9] Deployment costs that vary with the size of customer base include customer premise equipment—modems, network cards and radio dishes—as well as network-side investments such as DSLAMs and cable head-end equipment. These costs will also fall over time along as, for example, options for customer self-installation are perfected. Customer acquisition costs tend to vary with customer base as well, but they may not fall as quickly under competition since we would expect an increase in customer churn. They will also differ across carriers as it is likely to be cheaper to migrate an existing non-

majority of deployment costs are fixed and sunk. The incremental cost of adding broadband capability to an incumbent's network tends to be much less than that for green field construction.[10] Given any specific geographic market, deployment cost of incumbent carriers will also depend on the inherent characteristics of their respective broadband technologies as well as their network footprints. For instance, cable systems have a greater presence in residential neighborhoods and rural areas whereas the telephone network is relatively better represented in densely populated areas such as central business districts. DSL more often has an attenuation problem in residential areas, especially low-density suburbs and rural areas, where loop lengths are the longest. CM service requires an upgrade to hybrid fiber-coax network so as to enable two-way data transmission. Wireless broadband technologies typically necessitate smaller outlays for facilities and equipment than fixed networks though the cost of licensing radio spectrum can eliminate this advantage.

Our model of a broadband race captures the fixed, sunk nature of deployment costs, the steady decline in those costs, and their differences across contenders. Other aspects such as uncertainty over the cost of alternative technologies are suppressed in favor of simplicity. Depending on the scope of the geographic market, the model can accommodate cases where just one of the incumbent networks is viable, as well as the more interestingly case where both vie to serve the market.

Policy Promoting Broadband Competition

As broadband services only recently reached mass market appeal, a variety of regulatory treatments can be found. Governments have taken a variety of policy approaches, ranging from forbearance to direct regulation of rates and investments. Even within the US, the 50 State commissions and the FCC exhibit disparity in their treatment of broadband services.[11] Some regulators require broadband tariffs—in some cases placing those services under price caps. Generally, ILEC provision of DSL service is the most common target of regulation, with cable modem and wireless broadband access receiving light regulation. Notably, implementation of the Telecommunications Act of 1996 (TA96) required ILECs to open their networks and unbundled network service elements (UNEs) for lease to competitive local exchange carriers (CLECs). One such unbundled element is the high-frequency digital portion of local loops. Such

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broadband customer to broadband service than to either attract a first-time user or poach extant broadband customers from rivals.

[10] Alternatively, these embedded networks were optimized to provide services that differ in several respects from broadband data access: local and long-distance networks are designed for voice telephony, and cable's hybrid fiber-coax network for broadcast of multi-channel video entertainment. In addition, green field deployment—such as the construction a next-generation optical fiber network—has much freedom to choose the serving territory, the network architecture and the transmission protocol without concern for compatibility with the legacy network.

[11] See Lee (2001) for a summary of state commission treatment of broadband services.

'line splitting' enabled service-based providers to offer high-speed access along with other telephony and/or video services, possibly provided using other unbundled elements, and especially UNE platforms. The Telecom Act also identifies a potential exemption from the unbundling mandates for, among other services, high-speed Internet access. In the FCC's implementation of Section 706, they allow ILECs to avoid unbundling their high-speed facilities when they structurally separate their data affiliates from telephone operations, supplying competing carriers with parity service to their broadband affiliate.[12]

Typically, cable provision of high-speed Internet access is lightly regulated. Recently the FCC declared cable modem an 'information service', and hence beyond its regulatory reach, only to have the decision subsequently reversed by an appeals court. Whatever the outcome of federal treatment, local municipalities have considerable power to regulate CM service deriving from their authority to award operating franchises. The principal concern here is how franchise boards have placed new conditions on their franchisees, and in several highly visible decisions, have forced cable franchisees to provide nondiscriminatory access to all ISPs as well as their affiliated ISPs. Neither cable franchise authorities nor state and federal regulators have required operators to unbundle cable modem service and to offer high-speed data transmission to unaffiliated service providers. Nevertheless, as is shown below, regulation of cable video services can indirectly impact broadband deployment decisions.[13]

Opening of broadband facilities and unbundling high-speed services is the first of two essential elements of an open access policy. The other component is the pricing of the network services used by service-based providers. Pricing rules impact an incumbent's incentive to build a broadband network as well as the incentives of rival carriers to purchase its network services. These rates could be set unilaterally by the incumbent or privately negotiated between the carriers. We will assume that a regulatory authority sets wholesale rates although we will not model that process explicitly. The analysis will be guided by two popular wholesale pricing methodologies: the Efficient Component Pricing Rule (ECPR) and Long Run Incremental Cost (LRIC) pricing. The FCC devised a version of LRIC, called Total Element LRIC to price network elements and imposed this methodology on states that did not develop their own approach. Generally speaking, ECPR ensures the facility owner is compensated for profits on sales lost to downstream competitors, whereas LRIC pricing makes no such guarantee. Nevertheless, we will assume in our analysis that facility owners will not voluntarily unbundle their broadband networks and lease them to service-based rivals.

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[12] SBC has, for instance, chosen to place all its broadband data services in a separate subsidiary, Advanced Solutions, Inc.

[13] While the 1996 Telecommunications Act eliminated (as of February 1999) federal regulation of rates for cable TV services that had been enabled by the Cable Act of 1992, States and municipalities still retain some authority to regulate cable TV rates. Also, the FCC continues to impose 'must carry' obligations on cable operators whereby they retransmit qualifying local over-the-air programming.

Of course, in the short run, resale provides another means by which competing providers can exert discipline on incumbent carriers, at least in limited terms, based on price and service characteristics. Resellers, like all service-based providers, trade off the cost and risk associated with constructing a network against the wholesale rates they pay for using the incumbent's facilities, in addition to lack of control over network capabilities. The opportunity to provide broadband service without investing in facilities gives service-based providers a 'real option' that can be 'called' when realized demand or cost conditions are out of line with expectations.[14] Pricing rules that ignore this option value will skew incentives to undertake such large, sunk outlays, causing incumbents to curtail or delay the investment, or in the extreme, to forgo the expenditure entirely.[15]

A Technology Race Model of Broadband Deployment

Here we modify the standard model of a 'technology race' to capture essential features of broadband deployment decisions.[16] The model is sufficiently flexible to accommodate key features of regulatory policies aimed at promoting broadband investment. Each firm has the strategic timing problem of deciding if and when to deploy a broadband network. If they should do so, they incur a one-time,[17] fixed cost[18] that varies by firm and the date of deployment: $c_i(t)$ is the nominal cost of broadband deployment for Firm i at date t. Due to continuous improvement in microelectronics, optics, radio technology, software and other enabling technology, (nominal) deployment cost falls over time at a decreasing rate:

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[14] Hausman (2000) and Pindyck (2004) show how unbundling creates a real option that derives from the sunkness of investment and the uncertainty of future costs. They go on to demonstrate how TELRIC pricing under compensates an incumbent for its investment relative to competitive returns. This modeling approach does not draw conclusions about the equilibrium timing of deployment decisions.

[15] A related concern is that, compelled to open its facility, an owner will degrade access service to a competitor, or find another means to disadvantage rivals relative to its service. Open access rules seek to address such concerns via nondiscrimination provisions.

[16] See Katz and Shapiro (1987) and Fudenberg and Tirole (1985) for general formulations of a technology race between contestants. Here some of Fudenberg and Tirole's notations are adopted. For an application of the technology race model to a context similar to this one, see Riordan's (1992) model of video competition between telephone companies and cable operators and its regulation.

[17] In reality, construction of any network is a gradual process during which firms will incur adjustment costs. In that case, firms also must tradeoff the high cost of faster deployment costs more in present value (or sacrifice quality of the network) compared to that for slower deployment.

[18] Faulhaber and Hogendorn (2000) model staged broadband competition in which carriers decide how much capacity to build, as well as, the extent of territory served.

$c_i'(t) < 0$ and $c_i''(t) > 0$. Deployment costs asymptotically approach a lower bound: $C_i > 0$. The bounds are low enough to allow at least one firm to find broadband deployment profitable. Costs are allowed to vary across firms reflecting differences in their embedded networks and the technology to upgrade to broadband. This variation is an important source of determining the equilibrium order of deployment. Finally, assume that deployment costs $c_i(0)$, are so high that no firm finds deployment profitable, even if it were the sole broadband service provider. Further, deployment costs are assumed to not depend on any firms' past occurrences of broadband investment—ruling out, among other phenomenon, the possibility of 'learning by building.'

Falling deployment costs pose broadband contenders with a tradeoff between lower costs from waiting against the risk of being preempted by a rival. Each firm's profit in a given period depends on the industry profile at the moment in terms of broadband supply. When more than one firm offers broadband service in a market, they share in the broadband revenue according to the intensity of retail competition.[19] The dependence of firms' operating profit on past deployment history is indicated by $\pi_i^h(t)$, where *h* captures the history of past deployment by all firms in the market. It is important to note that this expression includes operating profits from non-broadband operations. For instance, it would include traditional switched voice revenues for a local telephone company and video revenues for a cable TV operator. When there are two facilities-based firms, as in the case of a telephone and a cable company, let $h = n$ to indicate that neither one has deployed, $h = 1$ (2) that just Firm 1 (2) has deployed, and finally $h = d$ that there are dual networks deployed.

Generally, the $\pi_i^h(t)$ s are increasing over time, reflecting a steady increase in service demand—typically driven by growth in the number and quality of broadband applications and content (e.g., multimedia games, video conferencing and VoIP services), and also word-of-mouth communication and network effects stemming from user file sharing (e.g., digital photographs and videos). As written, dual-deployment profits π_i^d are invariant to the order in which firms choose to deploy, in which case no permanent advantages derive from being a leader or a follower. Since, furthermore, profits do not depend on the timing of the deployments, first-mover advantage gained through customer lock-in or brand equity is ruled out. The provision of broadband service adds to operating profit of the carrier who deploys the necessary facilities: $\pi_i^i(t) > \pi_i^n(t)$ and $\pi_i^d(t) > \pi_i^j(t)$. It is reasonable to assume that the baseline profits prior to deployment, $\pi_i^n(t)$, grows rather slowly since those revenues derive from mature service markets. In comparison, post-deployment profit, $\pi_i^i(t)$, should track the growth rate in aggregate demand for broadband services. A firm's operating profit is likely to fall when its rival deploys broadband technology even if it has not entered that market

[19] In this way, the model differs from patent race models in which the winner takes all.

yet: $\pi_i^j(t) < \pi_i^n(t)$ and $\pi_i^d(t) < \pi_i^i(t)$. Through marketing and bundling of narrowband and broadband services, a laggard suffers loss of customers to its broadband rival: $\pi_i^n(t) > \pi_i^j(t)$.

Duopoly Broadband Race Equilibrium

Contestants choose a timing strategy or rule specifying the build date given history to that time. With knowledge of deployment times, firms can compute their discounted profit. If there is no competitive threat, a firm chooses the best time to lead, denoted: t_i^l. This occurs when the incremental operating profit from deployment equals a measure of the dynamic marginal cost of deployment:

$$L_i(t) = \pi_i^i(t) - \pi_i^n(t) = rc_i(t) - c_i'(t)\,. \tag{13.1}$$

Refer to $L_i(t)$ as the leader's incentive. It measures the increment in operating profits when the firm is the only one to deploy broadband services. The best time to follow, t_i^f, conditional on the other firm having deployed, obeys a similar rule:

$$F_i(t) = \pi_i^d(t) - \pi_i^j(t) = rc_i(t) - c_i'(t)\,. \tag{13.2}$$

Here $F_i(t)$ is the follower's incentive. The best time to follow is independent of the date of first deployment, signifying there are no spillovers from the leader to the follower.

The leader and follower dates do not determine the equilibrium dates because, while a firm might choose to deploy earlier whether it is a leader or follower, its rival may prefer not to assume the remaining position in the order of deployment. To sort this out, define a carrier's preemption time, t_i^0, as the time when Firm *i* is indifferent between leading at that date and, instead, allowing its rival to lead at that same date. With this notation it is stated that the main result on equilibrium in this two-player timing game, renumbering the firms if necessary: If $t_1^0 < t_2^0$ and $t_1^l < t_2^l$, then, at a sub-game perfect Nash equilibrium, Firm 1 deploys first at the earlier of the dates, t_2^0 and t_1^l, while Firm 2 deploys second at time t_2^f. In words, when Firm 1 is the more eager to deploy, it will deploy first in equilibrium, but not necessarily at the time that yields it maximal profits. Instead, it deploys an instant before its rival finds it preferable to be the leader rather than being relegated to the role of the follower. To wait beyond the rival's preemption date, the firm risks having the lead stolen. The assumption that contestants react quickly to deployment decisions is crucial to arriving at this equilibrium as Fudenberg and

Tirole (1987) emphasize.[20] Within a single market, the winner may take all in this race. Once a carrier has deployed a broadband network, a complete overbuild is not profitable as the providers enter into a price war. Households are unlikely to subscribe to more than one broadband Internet access service. Alternatively, dual subscription may not be rare among business customers. Furthermore, depending on the technology, the costs may not be great to build a network that merely 'passes' subscribers in an area, without incurring the additional investment necessary to connect users. Finally, differentiation in the broadband services is inevitable given the differences in technology.

Comparative-static Analysis

Clearly, both market demand and firm cost conditions affect deployment timing. Open access policy alters these conditions and, hence, the equilibrium timing of broadband deployment. To conduct these exercises, label, without loss of generality, Firm 1 as the leader when no open access is imposed, and Firm 2 the follower. Let the baseline market condition be such that both firms eventually deploy a broadband network in absence of open access. Then formally the effect of an open access rule expressed as a perturbation in the profit path of both firms during the monopoly period (when just one firm has built a network and offers broadband service) and the dual deployment period (when both firms have built networks): $\pi_i^h(t) + \varepsilon\delta(t)$ where $\varepsilon > 0$ and $\delta(t) > 0$ for t in the relevant range and $h = i$ and d. Next, examine the local impact of open access rules when ε is arbitrarily small.

Simple comparative static exercises provide the impact of open access rules. Of particular interest is how the deployment pattern is affected by the levels of operating profits. In the Appendix some comparative static results are calculated. Those results are summarized below in Table 13.1. Effects of changes in deployment costs are somewhat less useful. By specifying a functional form for the deployment costs, comparative static effects are derived. The table entries are reasonably intuitive. For instance, lower construction costs—both in terms of absolute level and also the dynamic marginal cost—accelerate deployment dates.

Table 13.1. Comparative-Static Analysis of Broadband Race Operating Profits

	π_i^i	π_i^n	π_i^d	π_i^j	π_j^j	π_j^n	π_j^d	π_j^i
t_i^l	–	+	0	0	0	0	0	0
t_j^0	0	0	+	–	–	0	+/–*	+

[20] Allowing firms to be imperfectly informed as to rivals' progress on its construction program, or informed with a lag, is more realistic, but greatly complicates the strategic interaction of the timing game.

t_j^f	0	0	0	0	0	0	–	+

Note. * - according to whether $t_i^f < / > t_j^f$.

Regulation of Non-broadband Service

Next, consider the impact that non-broadband regulatory policy can have on the equilibrium of the broadband race. Somewhat surprisingly, the analysis finds that incentives to make broadband investments are affected by the regulatory treatment of other services provided by the incumbent carriers. For instance, regulations governing cable operator's video sales and a telephone company's rates for voice services affect the equilibrium deployment of broadband services indirectly. To begin, assume that regulation has the effect of reducing the operating profits of the two incumbents by a fixed amount and that this amount is constant over time and independent of deployment history. So, for instance, Firm 1's operating profits are reduced by a constant amount Δ_1 regardless of which, if any, firms have deployed a broadband network; and similarly Δ_2 for Firm 2 where the profit impact of regulation may differ by carrier. Clearly, this regulation has no effect on the timing of deployment, whether or not the lead firm, Firm 1, engages in preemption.

First, the timing of the first deployment is determined by the incentive to lead: $L_i(t) = \pi_1^1(t) - \pi_1^n(t)$. If profit is reduced by Δ_1 under either scenario, i.e., Firm 1 leads or neither firm deploys, then there is no change in the time of first deployment, t_1^l. Second, a similar result holds when preemption occurs. To see this, note that preemption time t_2^0 depends on the operating profits π_2^2, π_2^1 and π_2^d. Totally differentiating the preemption date when these profits are reduced by an amount of time, cancel each other out, resulting in no change in any deployment date.[21]

Regulators are not likely to intervene in these markets in such a symmetric way, however. If broadband capabilities invite any regulatory intervention, overall firm profits will be more constrained after deployment than before. Broadband services are provided using at least some of the network assets built to provide narrowband services. Any regulation that allocates some portion of the cost of these facilities to broadband, in addition to investments that are directly attributable to broadband services, will make narrowband services appear more profitable. In that case, the constraint on profits will tighten after a firm has deployed broadband services.

[21] Of course, profit regulation could be made conditional on the level of competition in the industry so as to either accelerate or impede deployment. The interest here is in policy that appears neutral toward broadband investment decisions.

To be precise, suppose regulation reduces profits by Δ' before a firm's broadband deployment and by Δ'' afterwards, where $\Delta'' > \Delta'$. Even when the two providers are treated symmetrically, so that their profits are reduced by the same amounts, this regulatory rule results in delay of deployment. It is easy to show that both t_1^l and t_2^0 increase, so that first deployment is delayed regardless of whether the leader engages in preemption. Even though broadband services are not directly regulated, by penalizing broadband deployment through the cost allocation rule applied to narrowband services, both firms are less eager to make the necessary investment. Direct regulation of retail and wholesale broadband services are not the only means to affect their deployment. Regulation of a service that was related to broadband services through an artificial cost allocation rule is also examined. Alternatively, regulation to a non-broadband service that is complementary in demand to broadband Internet access (or a close substitute such as ISDN) could have been applied to arrive at the same conclusion. This exercise suggests that, given existing regulatory institutions, non-regulation of broadband service may be a policy maker's chimera.[22]

Open Access Rules and the Equilibrium Broadband Race

Open access rules vary across several dimensions. Which facilities-based broadband providers must grant access, the first firm to build a broadband network, or any firm that eventually builds such a network? Who is assigned rights to access existing broadband facilities, other facilities-based carriers who have built (or potentially could build) a broadband network, or service-based providers who resell broadband services? When must access be granted? Open access could be required immediately upon completion of the broadband facilities, or there could be a delay. Additionally, mandates to share facilities could expire once infrastructure competition is realized. Finally, on what terms must facilities owners supply wholesale broadband services? A wide range of pricing methodologies lie between the ECPR and LRIC principles.

In this section alternative open access rules are specified and their impact on the broadband race is assessed. Comparing the outcome of the race with and without an open access rule reveals its impact on deployment pattern relative to the outcome without sharing. It is important to remember that this benchmark case is not necessarily welfare optimal. Since firms find themselves in a winner-take-most contest, preemptive tendencies may cause investment to occur too soon relative to the welfare optimum.[23]

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[22] See, for example, Oxman (1999).

[23] At bottom, the firms have no means to express the value they attach to deploying at specific times, except to actually make the expenditure. Suppose, for instance, the first firm derives its highest profit by deploying in year 1 which is much lower than the highest profit the second firm can generate, and which is realized only when that firm deploys in year 2. In absence of an auction of the right to deploy at the preferred time, the

Resale of Monopoly Broadband Service

Our analysis begins by considering the case of a single infrastructure owner who is forced to share its network with a single service-based rival immediately upon completing the broadband upgrade. This situation arises in markets where the local telephone company does not encounter a cable TV system or a wireless network capable of upgrading to broadband service. In absence of an open access obligation, the incumbent network (Firm 1) deploys broadband services at its stand-alone profit-maximizing date t_1^I. Then suppose that it must lease the use of its network to a service-based firm who can then offer undifferentiated broadband services.[24] Provided lease rates do not preserve monopoly levels of incumbent profits, and assuming that the reseller enters at its first opportunity, deployment will reduce incumbent profits. Then, by inspection of Eq. 13.1, the decline in operating profits results in a delay in deployment date t_1^I.

It is entirely possible that the reduction in incumbent operating profits caused by open access will be so large that the incumbent will decline to upgrade to broadband altogether. This is likely to occur in markets that are marginally profitable on a long run basis to begin with, such as rural areas. Open access in this situation only decreases the likelihood these customers will be served by advanced services. It is important to note that we assume away any additional cost incurred as a result the opening by the facilities-based carrier. In fact, the cost of deploying an operations support services to enable resale can be substantial and would further reduce incumbent incentives to deploy.

This conclusion reverses the otherwise robust result of Gilbert and Newbery (1982). In that paper, they find that an incumbent will adopt the innovation before an entrant and earlier than it would have but for the threat of entry. Their result derives from the fact that competition necessarily dissipates profits; the prospect of forgoing its monopoly rents spurs the incumbent to adopt earlier. In the current setting there is a competitor, but because it resells the incumbent's service, it cannot pre-empt the incumbent. The incumbent has complete control over if and when it faces retail competition—even if it does not control resale rates—because competition is possible if and only if the incumbent deploys a broadband network. The delay caused by open access would not be eliminated, but it may be reduced,

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first firm may preempt the second firm if the first firm would earn much lower profit if it were to wait until year 2. This would be inefficient if total welfare was roughly proportional to firm profits.

[24] Were the reseller to differentiate its broadband service some how, overall industry profits could increase with competition, and the incumbent could take a share of the incremental profits via higher lease rates. In fact the opportunity for product differentiation is minimal under pure resale, in which case retail competition necessarily reduces industry profit below the monopoly level.

were the incumbent to enjoy a monopoly over broadband services for some period of time before resale was required. The interim monopoly profits would then reward it for earlier deployment. Indeed, as the grace period is extended indefinitely, the timing of deployment would converge to the monopoly case. The rationale for such an approach is exactly the same as the patent system which gives the patent holder a monopoly over the use or licensing of the technology.

Interim Facility Sharing

Consider now an open access rule that allows a follower to use the leader's broadband facility until that time when it builds its own facilities.[25] No pure reseller is allowed to enter to use the available broadband facility; only a 'committed entrant' that already owns a network and has the potential to upgrade to broadband has that right—though it may choose never to do so.[26] The interim period during which access to the facility is required ends when broadband platform competition is realized with a second deployment. This scenario, translated into technology race framework, raises profitability of the latecomer during the monopoly period: $\Delta\pi_i^j > 0$. Notice that the profits of the leader increase for both firms—even while Firm 1 is assumed never to follow. This out-of-equilibrium strategy will nevertheless alter deployment incentives. Next, consider the case when profits of the leader are unaffected by open access: $\Delta\pi_1^1 = \Delta\pi_2^2 = 0$. The interpretation of this additional assumption is that the facilities-based provider remains 'whole' as if prices are set according to ECPR, either by a regulator or the self-interested firm. Besides these changes, profits after second deployment are assumed to be unchanged since the follower can no longer lease first-mover's facilities: $\Delta\pi_1^d = \Delta\pi_2^d = 0$. In this case the impact of open access is quite simple to derive and intuitive to explain. Firm 2's preemption date, the timing of the first deployment, is delayed as a result of the increase in profits derived from resale: $\Delta t_2^0 > 0$. Furthermore, the date at which Firm 2 follows is also delayed: $\Delta t_2^f > 0$. Thus, the option to lease the leader's network slows down

[25] Derivations supporting the comparative dynamic claims appear in the Appendix.

[26] Note that it may be less costly for one of the firms to lease the other's network, and this should be reflected by some differential cost of service-based broadband provision. An example would be the fact that the telephone network in most cases is designed around industry technical standards that do not vary from one region to another. Cable TV systems, in contrast, adhere to a variety of technical specifications which would make it more costly for a service-based competitor to make use of a rival's network. This situation is changing, e.g., Cable Laboratories has defined and promoted its DOCSIS (Data Over Cable Service Interface Specification) standard. Standardization could make it more attractive to lease access from a cable operator were they compelled to unbundle their network services.

both deployments.[27] The follower is now more profitable prior to deploying its broadband facilities, and as a result, puts off its deployment date. The leader also delays its deployment—which occurs at the follower's preemption date—because the follower is less threatening.[28] Of course, the magnitude of the impact of open access rule depends on how profitable it will be for the follower to lease the leader's network, i.e., the size of $\Delta\pi_2^1$. This profit increment would shrink, e.g., if the follower was precluded from leasing the leader's broadband network for some fixed period, akin to the exclusivity period of a patent. If the period of exclusivity is short, then the results continue to hold qualitatively. Since the profit increment from following does not change as a result of an exclusivity period, Firm 2 will not alter the date at which it follows. However, forgone profit during the exclusivity period will reduce its overall profit from following (relative to open access without an exclusivity period), and so the preemption date will occur a bit earlier.[29]

Now suppose that we also increase Firm 1's profit to reflect the possibility that it, too, could earn higher profits should it instead follow the lead of Firm 2: $\Delta\pi_1^2 > 0$. In fact, assuming the order of deployment does not change, Firm 1 would never be in a position to realize these profits. But the prospect that Firm 2 could lead, and that an open access rule would make Firm 1 a slower follower, has the effect of advancing Firm 2's preemption date. If Firm 1, the actual leader, engages in preemption, then this effect taken by itself will speed up the initial deployment, $\Delta t_2^0 < 0$, just the opposite direction from the previous case. The net effect of this more symmetric open access rule is ambiguous, depending on several factors. The earlier conclusion that both deployment dates are delayed is preserved if the Firm 2 derives relatively more profits from reselling than Firm 1.

Further, suppose that during the interim period of sharing, the leader's profits are not unaffected but are reduced below their unregulated levels: $\Delta\pi_1^1 < 0$ and $\Delta\pi_2^2 < 0$. The interpretation of this possibility is that access prices shift some of the profits from the facilities-based leader to the service-based follower. This occurs, e.g., if regulators imposed some form of LRIC pricing. The effect of this form of open access, as might be expected, delays deployment as now the leader has reduced incentives to invest. To simplify analysis of this case, return to the

[27] If, instead of preemption, Firm 1 would lead at its preferred time, then this policy would have no effect on the initial deployment. That would not, however, change the fact that the second deployment is delayed.

[28] The higher profits to Firm 2 during the monopoly period raises the value of following independent of the first deployment because all other profit levels are unchanged for Firm 2, and the only way it takes advantage of the reselling profits is by being a follower. The equality of Firm 2's profits of leading and following is restored when the first deployment is delayed because the analysis starts from a time earlier than Firm 2's monopoly deployment date.

[29] Of course, if the exclusivity period grows indefinitely long (beyond the duration of the unregulated monopoly period), then the open access rule becomes irrelevant.

asymmetric rule where Firm 1 alone is required to open up its network. The rule then redistributes profits from Firm 1 to Firm 2: $\Delta\pi_1^2 > 0$ and $\Delta\pi_1^2 < 0$. In that case, all three critical deployment dates are delayed: $\Delta t_2^0 > 0$, $\Delta t_2^l > 0$ and $\Delta t_2^f > 0$. Consequently, once again the first and second deployments occur later than at the unregulated equilibrium as a result of the open access rule.

Pure Broadband Resale

Another open access rule would reserve use of an incumbent's network to a pure reseller, denying access to another facilities-based incumbent. In practical terms, this would say the cable and telephone companies cannot gain access to each other's unbundled network services before or after they upgrade to broadband capabilities, but an independent service-based provider could lease either broadband network. This condition promotes open access as a means to stimulate downstream service competition, and not specifically to encourage potential infrastructure competitors. In terms of the broadband race, this rule uncouples the follower's decision to deploy broadband from its option to use the leader's network to provide service beforehand. If the reseller simply earns a profit, and the leader remains whole, e.g., using ECPR, then the pattern of deployment will not depart from the unregulated outcome. This rule becomes more interesting when, possibly through LRIC access pricing, the leader's profits are reduced during the monopoly period: $\Delta\pi_1^1 < 0$. This effect of this condition is to slow down deployment. In all cases the follower date is unchanged because incremental profits are independent of how much the leader earns. However, the leader's monopoly date and its preemption date are delayed, so assuming the open access rule is applied to both firms, the initial deployment will be delayed. This is true whether the leader pre-empts the follower, or is able to deploy at its monopoly time.

This characterization of this open access policy may be too limited. It could be the case that by signing up many customers for a particular technology, a reseller could aid the facilities-based carrier in defending against later competition from an alternative technology. Arguably, ILECs may stem the loss of DSL customers once cable modem service becomes available in a market if broadband data CLECs have signed up many DSL subscribers in the meantime. To capture this feature profits need to be redistributed from the follower to the leader after the second deployment.

Symmetric and Asymmetric Facility Sharing

Next, we examine the effects of allowing the follower to continue to lease the leader's network *after* the follower builds its broadband facilities. A justification for such a rule rests on the need for additional profit to reach platform competition. The rule gives the follower greater freedom in making its buy-build decisions, thereby lowering its overall costs at the expense of the leader's profits.

Below, a more symmetric version of this rule gives both firms rights to lease the other's facilities. When just the follow has this right, the open access rule increases the follower's profits during the dual-deployment period as well as during the leader's monopoly period: $\Delta\pi_2^1 > 0$ and $\Delta\pi_2^d > 0$. The analysis is simplified by assuming no reduction in the leader's profit in either period, as if the ECPR was applied. It can then be shown using the comparative statics results that the effect of these profit changes will unambiguously delay the follower's preemption date: $\Delta t_2^0 > 0$. Assuming that the leader will pre-empt the follower, this open access rule works to delay initial deployment. Also, if the increase in profits is roughly the same in both cases, then there is no effect on when the follower deploys since the net effect on the incentive to follow is unchanged: $\Delta t_2^f = 0$. Contrary to intent, the rule does not accelerate subsequent deployment.

This latter open access rule is highly asymmetric. If its intent is to improve incumbent networks' buy-build decisions, the sharing of the broadband facilities should be more symmetric. To examine this possibility, suppose that there is no open access during the monopoly period, but once the two broadband networks have been built, both firms can lease the other's broadband network.[30] Here the focus of the rule is directly on improving the buy-build decisions. The effects of this rule are characterized by assuming: $\Delta\pi_1^d > 0$ and $\Delta\pi_2^d > 0$. By increasing the profits from dual-deployment, the date at which either firm would follow the leader is advanced since the profit incentive to follow has increased. The effect on the follower's preemption date depends on the exact size of the profit changes. In fact, if the two carriers are treated symmetrically (in that their profits rise the same absolute amount), then there is no change in the preemption date. However, these same changes will unambiguously delay the preemption date for either firm: $\Delta t_i^0 > 0$. This will not be critical unless it had the effect of reversing the order of the leader and follower. If Firm 1's preemption date is delayed long enough, then in equilibrium it could become the follower, Firm 2 would assume the role of the leader, deploying at preemption date t_i^0. Here is one case when an open access rule could result in the apparently more efficient technology being deployed second, or potentially, not at all.

Conclusions

This study analyzed the impacts of alternative open access rules using an equilibrium model of the broadband deployment race. The rules altered deployment timing by two or more contestants, typically resulting in delay in either the first or second deployments, or both. Delays can be traced back to reduced incentives to invest in broadband facilities relative to service-based

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30 As before, assume that leasing broadband network services does not reduce the facility owner's profit as if ECPR pricing is used.

alternatives, or relative to no investment. It is also found that asymmetric treatment of carriers, and hence their corresponding technology, can have significant effects on the pattern of deployment even while intervention in this new service market can be quite subtle and indirect.

Our analysis of the open access rules is limited to assessing their impact on timing of broadband deployment, and its implications for technology choice. A more complete analysis would evaluate the rules in terms of their impact on social welfare. As formulated, the technology race model lacks sufficient detail to conduct a full welfare analysis of the different open access rules.[31] It is reasonable to assume, however, that the more broadband carriers that serve the same market—whether they own facilities or resell incumbent services—the lower prices are for broadband service. Assuming narrowband rates are not affected, it is concluded that welfare rises with either form of competition. To the extent that open access rules tend to delay deployment of broadband service, consumer welfare is foregone. Alternatively, this outcome must be compared against the alternative where a monopolist deploys earlier, but also sets monopoly prices throughout.

Certainly the welfare costs associated with deployment delays should factor importantly in the debate over the form of open access rules applied to broadband infrastructure. Indeed, the cost of delays in deploying other new telecommunications technology is large.[32] Nevertheless, this calculus may miss other welfare costs stemming from reduced pace of innovation in broadband technologies. First, it is likely that each generation of broadband technologies builds upon the previous generation, learning from earlier mistakes. Deployment delays only retard the rate at which this knowledge accumulates. Furthermore, since new technology often rides on at least some portion of existing infrastructure and customer equipment (as in the case of DSL and cable modem technology), when investment is delayed and the current network is being amortized, so too may be the date when new technologies are deployed by upgrading or retrofitting existing infrastructure. Finally, the incentives for investing in R&D may be blunted depending on how open access rules alter rates of return on broadband investment. All of these considerations argue for an expanded analysis of the broadband race beyond modeling incentives to commercialize proven technology.

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[31] Owen and Rosston (2003) undertake a welfare analysis of an open access called ‘net neutrality,’ focusing on the implications for transaction costs.

[32] See Rohlfs et al. (1991), Baer (1995) and Hausman (1997).

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Appendix

Suppose that the first and second deployments occur at t_1 and t_2, respectively. Then, if firm k $(= i \text{ or } j)$ deploys first at t_1, and the remaining firm deploys at t_2, Firm i's discounted operating profit is given by:

$$\Pi_i^k(t_1,t_2) = \int_0^{t_1} \pi_i^n(t)e^{-rt}dt + \int_{t_1}^{t_2} \pi_i^k(t)e^{-rt}dt + \int_{t_2}^{\infty} \pi_i^d(t)e^{-rt}dt \qquad (13.A1)$$

where $j = i$ when Firm i leads, and $k = i$ when it follows. Notice how firms visit each of the three levels of operating profit, $\pi_i^n(t)$, $\pi_i^k(t)$ and $\pi_i^d(t)$ during the intervals $[0,t_1)$, $[t_1,t_2)$ and $[t_2,\infty)$, respectively. To arrive at Firm i's net payoff, simply deduct the present value of deployment cost from Eq. 13.A1:

$$\Pi_i^j(t_j,t_k) - c_i(t_i)\exp(-rt_i)\ . \qquad (13.A2)$$

Suppose, for the moment, that Firm i was certain that Firm j would deploy at t_j. Then Firm i's best time to lead maximizes:

$$\Pi_i^i(t,t_j) - c_i(t)\exp(-rt) \qquad (13.A3)$$

over the range $t < t_j$. The solution, t_i^l, satisfies a simple first-order condition:

$$(\pi_i^i(t) - \pi_i^n(t))e^{-rt} = (rc_i(t) - c_i'(t))e^{-rt}\ . \qquad (13.A4)$$

The left-side of Eq. 13.A4 is the (discounted) incremental operating profit from deployment. It is graphed as an increasing curve in Figure 13.1. The right-side of

Eq. 13.A4 is the (discounted) incremental savings in deployment cost from waiting, and equals the amortized cost less the marginal cost of deploying. It is represented by the falling curve in Figure 13.1. Call $L_i(t) = \pi_i^i(t) - \pi_i^n(t)$ the leader's incentive. From the figure, observe that t_i^l decreases as the curve shifts up. This makes sense since higher rewards for innovation should speed up their introduction. Reductions in incremental deployment cost have the same effect. The firm will choose never to lead if, in all periods *t*, $L_i(t) < rC_i$, the amortized minimum deployment cost. The optimal time for Firm *i* to follow (assuming Firm *j* will lead at a predetermined time) is defined analogously. The date t_i^f is found by replacing the leader's incentive with the follower's incentive $F_i(t) = \pi_i^d(t) - \pi_i^j(t)$. Finally the firm never follows if $F_i(t) < rC_i$ for all *t*. Notice that t_j is entirely absent from the marginal condition Eq. 13.A4. As a result, the rival's timing has no effect on either solution, t_i^f or t_i^l. Nevertheless, a firm's total profit is a function of t_j as can easily be seen from Eq. 13.A1. For this reason, a firm's fortunes crucially depend on when its rival deploys because that determines whether it will be a leader or a follower. Thus, firms battle for position in the order of deployment, but given that position, the timing of their deployment is not a strategic concern. This distinction becomes clearer when the strategic game is constructed. But before doing so, one last critical date is needed.

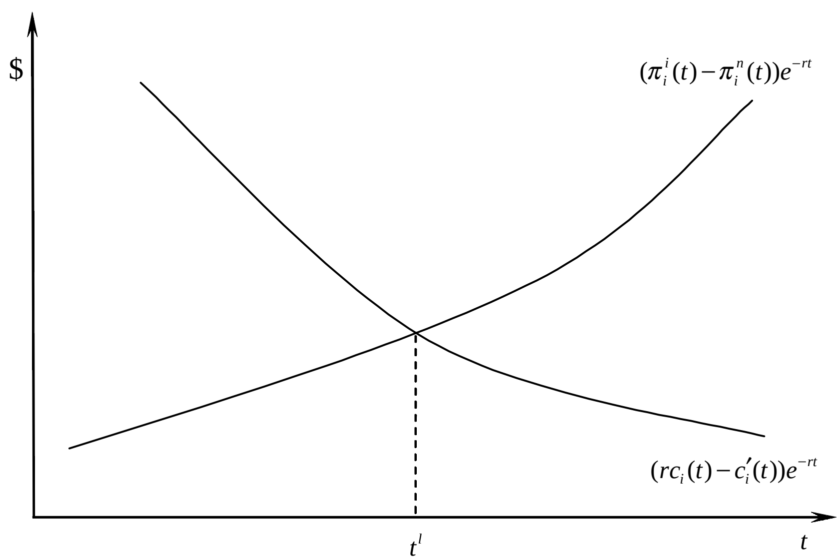

Fig. 13.1. Savings from Waiting and Marginal Deployment Costs

Given times when a firm wants to lead and to follow, there is some date when it is indifferent between the two roles. Offered the choice of being the leader by deployment at this preemption date t_i^0 or having its rival deploy at that time, payoffs are the same. The payoffs from each of these scenarios are expressed as follows:

$$\tilde{L}_i(t) = \Pi_i^i(t, t_j^f) - c_i(t)\exp(-rt)\,, \tag{13.A5}$$

$$\tilde{F}_i(t) = \Pi_i^j(t, t_i^f) - c_i(t_i^f)\exp(-rt_i^f)\,. \tag{13.A6}$$

Equation 13.A5 gives cumulative payoff to Firm *i* if it deploys at *t* while Firm *j* deploys later at t_j^f, and Eq. 13.A6 the payoff if Firm *j* deploys first at *t* while Firm *i* follows at t_i^f.

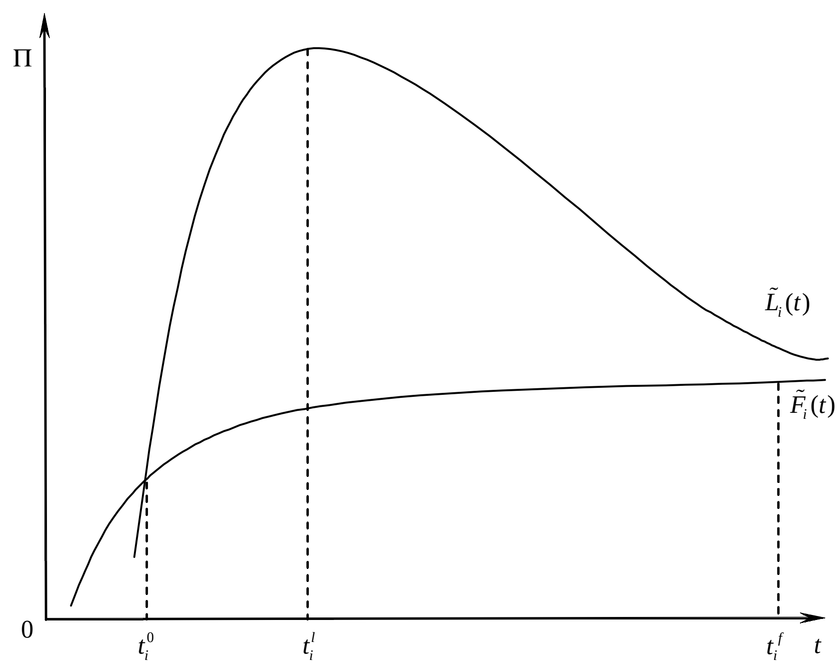

Fig. 13.2. Leader and Follower Incentives

As in Figure 13.2, $\tilde{L}_i(t)$ is single peaked at the preferred leader date, t_i^l. $\tilde{F}_i(t)$ increases over the region $[0, t_i^f)$ since a delayed first deployment postpones the date when the follower registers a profit decline. The preemption date equates the functions: $\tilde{L}_i(t) = \tilde{F}_i(t)$. Writing this equation and rearranging yields:

$$\begin{aligned} &P_i(t)\exp(-rt)/r - M_i(t)\exp(-rt_i^f)/r - F_i(t)\exp(-rt)/r \\ &\quad = c_i(t)\exp(-rt) - c_i(t_i^f)\exp(-rt_i^f) \end{aligned} \qquad (13.A7)$$

where $P_i(t) = \pi_i^i(t) - \pi_i^j(t)$ is Firm *i*'s preemption incentive, the difference between being a leader and a laggard; $M_i(t) = \pi_i^i(t) - \pi_i^d(t)$ is the imitation penalty imposed by the follower on the leader. This complicated expression simply balances the incremental revenue from taking the lead with the incremental cost, with all values properly discounted.

It is shown below that the preemption date t_i^0 is a decreasing function of $P_i(t)$ and $M_i(t)$ as well as $F_j(t)$ (through its dependence on t_j^f). Finally, t_i^0 is increasing (decreasing) in $F_i(t)$ depending on whether Firm *i* is a faster (slower) follower than *j*, i.e., $t_i^f < (>)\ t_j^f$.

Equilibrium Deployment

A strategy for each firm is a rule specifying whether or not to deploy in the current period given the history up to that time and given other firms' strategies. Within a period, firms move simultaneously. As usual players' strategies form a sub-game perfect Nash equilibrium when, in each and every sub-game, the continuation of players' strategies together form a Nash equilibrium. This equilibrium concept rules out deployment plans that would never be carried out but, if believed by rivals, could alter the equilibrium outcome. For instance, Firm *i* could not credibly claim to deploy in any period $t < t_i^0$ regardless of the history leading up to that time. Quite simply, it will lose money compared to never deploying. If Firm *i*'s preferred deployment date is very early (t_i^l occurs long before either t_j^l or t_j^0, then it will deploy at that time provided leading is more profitable than following, i.e., $\tilde{L}_i(t_i^l) > \tilde{F}_i(t_i^l)$. Its plans might be upset if its rival were also to find leading at that date more profitable than following, i.e., $\tilde{L}_j(t_i^l) > \tilde{F}_j(t_i^l)$, or equivalently, $t_j^0 < t_i^l$) since then Firm *j* will prefer to lead some time before that date t_i^l. By the same reasoning, Firm *j* cannot credibly commit to delay its deployment beyond its preemption date, t_j^0, because it could do better by taking the lead. As a result, Firm i is induced to advance its deployment date up to t_j^0 provided that it still prefers to lead. To sum, the general conclusion states that, if $t_i^0 < t_j^0$ and $t_i^l < t_j^l$, then equilibrium has Firm i deploy first at $\min\{t_i^l, t_j^0\}$ and Firm j follows at t_j^f.[33] Of course, the identity of the leader is an open issue. It depends on how operating profits and deployment costs affect the firms' relative leader and preemption dates. These dates depend, in turn, on the specific context of the application.

Comparative Statics

Simple comparative statics exercises establish the relation between the critical dates and the levels of operating profits and deployment costs. To simplify the derivations, assume that operating profits are constant over time: $\pi_i^h(t) = \pi_i^h$ for all t. From Figure 13.1 we observe that, even when operating profits vary over periods, t_i^l and t_i^f decrease in $L_i = \pi_i^i - \pi_i^n$ and $F_i = \pi_i^d - \pi_i^j$, respectively. This implies that t_i^l is decreasing in π_i^i and increasing in π_i^n. Similarly, t_i^f is decreasing in π_i^d and increasing in π_i^j.

Pictures are less convincing for the effects on the preemption date. Therefore, totally differentiating $\tilde{L}_i(t) = \tilde{F}_i(t)$ around t_i^0, and applying the Envelope Theorem provides:

$$dt_i^0 / d\pi_i^i = (\exp(-rt_j^f) - \exp(-rt_i^0)) / rD, \tag{13.A8}$$

$$dt_i^0 / d\pi_i^j = (\exp(-rt_i^0) - \exp(-rt_i^f)) / rD, \tag{13.A9}$$

$$dt_i^0 / d\pi_i^d = (\exp(-rt_i^f) - \exp(-rt_j^f)) / rD, \tag{13.A10}$$

$$dt_i^0 / dt_i^f = 0, \tag{13.A11}$$

$$dt_i^0 / dt_j^f = -(\pi_i^i - \pi_i^d) \exp(-rt_j^f) / D, \tag{13.A12}$$

where $D = -(\pi_i^i - \pi_i^j - (rc_i - c_i')) \exp(-rt_i^0)$. As long as $\tilde{L}_i(t)$ cuts $\tilde{F}_i(t)$ from above in the vicinity of t_i^0, as in Figure 13.2, then $d\tilde{L}_i(t_i^0)/dt > d\tilde{F}_i(t_i^0)/dt$ which

[33] Proved in Katz and Shapiro (1987).

ensures that the bracketed term in the expression for *D* is negative, and hence, *D* itself is positive. From Eq. 13.A8 and Eq. 13.A9 it is concluded that $dt_i^0 / d\pi_i^i < 0$ and $dt_i^0 / d\pi_i^j > 0$, provided that the preemption date precedes the follower's date for both firms, i.e., $t_i^0 < t_i^f$ and $t_j^0 < t_j^f$. Examining Eq. 13.A10, finds that $dt_i^0 / d\pi_i^d$ is positive or negative depending on whether t_i^f is earlier or later than t_j^f, respectively. Therefore, an increase in dual-deployment profits will delay the preemption date if, in popular terminology, the firm is a 'fast second' compared to its rival. Finally, from Eq. 13.A12, $dt_i^0 / dt_j^f < 0$ since $\pi_i^i > \pi_i^d$. These results are collected in the table found in the main text.

To assess the effects of changes in entry costs, the function $c_i(\,)$ could be perturbed however, instead an exponential form $c_i(t) = a_i \exp(-b_i t) + C_i$ is specified, and changes in its parameter values are considered. Substituting this expression into Eq. 13.A4 yields a closed-form solution to the leader and follower dates:

$$t_i^l = (1/b_i)\log(a_i(b_i + r)/(L_i - rC_i)), \quad (13.A13)$$

$$t_i^f = (1/b_i)\log(a_i(b_i + r)/(F_i - rC_i)), \quad (13.A14)$$

Simple inspection reveals that both t_i^l and t_i^f are increasing in the entry cost parameters a_i and C_i. The effect of b_i is only slightly less transparent. Differentiating Eq. 13.A13 gives:

$$dt_i^l / db_i = (t + 1/(b_i + r))b_i, \quad (13.A15)$$

which is positive. The same holds for dt_i^f / db_i. The effects on t_i^f require some tedious calculations:

$$dt_i^f / da_i = (\exp(-b_i + r)t) - \exp(-(b_i + r)t)) / D > 0, \quad (13.A16)$$

$$dt_i^f / db_i = (a_i t \exp(-b_i + r)t) - a_i t \exp(-(b_i + r)t)) / D, \quad (13.A17)$$

$$dt_i^f / dC_i = (\exp(-rt) - \exp(-rt)) / D > 0, \quad (13.A18)$$

$$dt_i^f / da_j = -M_i \exp(-rt)(dt_i^f / da_i) / D < 0, \qquad (13.A19)$$

$$dt_i^f / db_j = -M_i \exp(-rt)(dt_i^f / db_i) / D < 0, \qquad (13.A20)$$

$$dt_i^f / dC_j = -M_i \exp(-rt)(dt_i^f / dC_i) / D < 0, \qquad (13.A21)$$

where $D = -r(P_i - a_i \exp(-rt) - C_i) > 0$ by second-order conditions. The only ambiguity appears in Eq. 13.A17: $dt_i^f / db_i > (<) 0$ according to $\log(t_i^l / t_i^f) < (>) (b_i + r)(t_i^l - t_i^f)$. These results are summarized in Table 13.2 below:

Table 13.2. Comparative Statics for Deployment Costs

	a_i	b_i	C_i	a_j	b_j	C_j
t_i^l	+	+	+	0	0	0
t_j^0	–	–	–	+	+/–*	–
t_j^f	0	0	0	+	+	+

Note. * - according to whether $\log(t_i^l / t_i^f) < (>) (b_i + r)(t_i^l - t_i^f)$.