Evolving Technologies and Standards Regulation

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This draft: March 2009

Abstract

Spectrum regulation necessarily involves some regulation of the technology that licensees can use. One commonly stated assertion is that a mandated single standard, the solution followed by the EU for 2G wireless, is a successful model for spectrum regulation. We argue that a single standard leads to a free riding problem, and thus to a significant decrease in marginal incentives for R&D investment. In this context, keeping two separate standards may be a *necessary evil* to sustain a high level of R&D expenditures. We also provide conditions such that a non-standardization equilibrium is better for consumers and for society as a whole.

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1 Introduction

Spectrum regulation necessarily involves some regulation of the technology that licensees can use. Beginning in the early 1990's, the US Federal Communications Commission (FCC), as well as regulatory agencies in other countries, have taken an increasingly market-based approach to determining standards for wireless communications. For the Personal Communications Services (PCS) spectrum auctions, the FCC, as well as Industry Canada and the Mexican CFT, all allowed winning bidders to deploy any technology compatible with the band plan, power and emissions restrictions. At one point there were four 2G technologies with virtually nationwide coverage in the US. In contrast, Europe, mandated that all firms allocated 2G spectrum licenses deploy only the GSM technology. For 3G, there were two main technologies deployed. However, despite significant pressure from the US government and from US firms, the EU mandated a single 3G standard. The EU seems to be taking a similar approach toward mobile television.

One commonly stated assertion is that the EU mandate of a single standard is a very successful model for spectrum regulation. However, economic analysis of this assertion is limited, and neither theory nor econometric evidence provide unambiguous support for it. The purpose of this paper is to formally examine the claim that standards regulation is welfare enhancing. We develop a model featuring non-cooperative R&D competition and cooperative standard setting. Contrary to the above view, we find that, under some circumstances, standards competition results in higher consumer surplus and social welfare than mandated standards. Moreover, market based standards generally result in faster innovation than standards regulation.

More specifically, we consider a world in which the relative quality of each standard evolves over time as a result of each firm's R&D expenditure. We argue that standardization — at least early standardization — leads to a free riding problem, and thus to a significant decrease in marginal incentives for R&D investment. In this context, keeping two separate standards may be a necessary *cost* to sustain a high level of R&D expenditures. Specifically, we consider a model such that myopic firms would always agree to standardization; but considering the dynamics of product innovation, in equilibrium firms opt for developing their own standard. We also provide conditions such that a non-standardization equilibrium is socially optimal.

■ **Related literature.** Several authors have dealt with the economic analysis of standard setting. Katz and Shapiro (1985), Farrell and Saloner (1985), and Arthur (1989) laid down some of the theoretical groundwork on the problem of technology choice and standardization. Closer to our paper, Choi (1996) considers the trade-off between the short-run benefits from standardization and the long-run benefits from experimenting with different technologies. Under certain conditions, he finds that ex post standardization is optimal (as is the case in our paper). In Choi's model, firms do not gain a competitive advantage from investing in different standards. The main benefit of a delay in standardization is in resolving uncertainty about the relative merit of each technology.

Nisvan and Minehart (2007) present a multi-period model of R&D with the possibility of firms sharing technology. Their setup is different from ours (for example, no profits are earned until all n steps of R&D are successfully completed; and the possibility of firm exit is explicitly considered). Moreover, their focus is also somewhat different (less on the benefits from standardization, more on the costs of product market collusion).

The paper is organized as follows. In Section 2, we outline some of the main milestones in the history of wireless telephony, with an emphasis on the process of standard setting and the persistent lack of a single standard. In Section 3, we introduce a model of R&D and standards setting and the main result of our paper: there are situations when, despite costless bargaining and market benefits from standardization, the equilibrium features multiple, incompatible standards. Section 4 extends the analysis to consider social welfare. We provide conditions such that an equilibrium with multiple standards is socially optimal. Section 5 provides a discussion of the main results and Section 6 concludes the paper.

2 History of wireless standards competition

Wireless telecommunications have a long history of standardization issues. First generation (1G) wireless mobile voice (and data) communications came under two different standards: Analog Mobile Phone System (AMPS) and the Nordic Mobile Telephone System (NMTS). AMPS was the mandatory North American standard. Most of the rest of the world, including Europe, was split between AMPS and NMTS (Gandal, Salant, and Waverman, 2003).

Starting in the early 1980s, four different second generation (2G) standards were introduced: GSM (often called Global System for Mobile Communications); TDMA (time division multiple access); iDEN; and CDMA (code division multiple access). GSM, TDMA and iDEN all divide a carrier channel into time slots, and digitally encode the signal on the time slots; they differ in the time division protocols used. CDMA, the latest standard to be developed, can usually pack more bits, or voice calls, into a given amount of spectrum than can GSM or TDMA.[1]

The European Union delegated standard setting to the European Technical Standards Institute (ETSI), which mandated GSM. In contrast, the FCC in the U.S. and regulators in other countries, including Australia, China India, and various South American countries have allowed operators to select their own standards based on economic or whatever criteria they wanted (Gandal, Salant, and Waverman, 2003; Cabral and Kretschmer, 2006). As a result, virtually all 2G networks in Europe are GSM, while elsewhere either the European policy was followed or there are competing standards. In the U.S., for example, GSM was the first 2G standard deployed (by Sprint in Washington, DC). TDMA and CDMA were introduced shortly thereafter (the latter by Sprint, GTE, Primeco, Bell Atlantic-NYNEX (all but Sprint are now part of Verizon Wireless) and Ameritech, among others).

At an early point of the development of third generation wireless (3G), there was a tentative accord for a single 3G standard. However, a number of European equipment vendors who dominated ETSI (namely Ericsson, Nokia and Siemens) decided on a variation of the original 3G standard, CDMA2000, which was developed by QUALCOMM. As ETSI sets standards policy for spectrum in the EU, European operators adopted a slight variation of the CDMA2000 standard, namely WCDMA.[2]

CDMA2000 is essentially an upgrade of second generation CDMA and is largely backwards compatible. WCDMA (also called UMTS) is a variation of the CDMA2000 standard. It is essentially incompatible with either CDMA2000 or second generation CDMA (Salant and Waverman, 1998, 1999). What we mean by incompatible is that handsets or chipsets meant to work on one standard will not easily work on the other one.[3] In addition,

1. iDEN was deployed specifically for refarming narrow slivers of spectrum previously used for trunk radio service.
2. The U.S. was able to successfully lobby the EU to reverse the decision to require all European Union national regulatory agencies (NRAs) to require the ETSI mandated standard (as this would be a violation of a US/EU competition policy treaty). However, the EU NRAs allocated frequency in a way that makes it difficult for anyone to deploy CDMA2000; and in fact no firm has done so in the 3G bands.
3. More specifically, WCDMA and CDMA2000 employ different protocols or coding systems for voice and data signals over the airwaves.

2G CDMA operators can easily upgrade to CDMA2000, merely by replacing some radio equipment at base stations and upgrading the software in the switches. By contrast, 2G CDMA operators cannot easily upgrade to WCDMA. Finally, for GSM operators the cost of upgrading to CDMA2000 or WCDMA is about the same.

From a non-traveling-user point of view, the costs of multiple incompatible standards may not be very significant. In fact, every user has universal access to other users, regardless of which network they are connected to. There may be connection charges, but these result from there being more than one network, not from there being more than one standard. A traveling user may incur additional costs insofar as roaming may be limited. For example, a U.S. user with a CDMA or CDMA2000 handset will not be able to use it in Europe. However, many GSM handsets that are sold to European users can also be used in the U.S.

The costs of multiple standards would then seem to be primarily borne by operators and equipment manufacturers. For example, the market for GSM handsets and terminal equipment is greater than that for CDMA based equipment, allowing for greater economies of scale in the former. For a chipset manufacturer like QUALCOMM, lack of standardization in 3G implies additional costs for various reasons: in addition to the loss of scale economies, a portion of its CDMA software must be re-written to work in WCDMA.

The above history of the wireless telecommunications industry leads to the puzzling question which motivates our analysis: If multiple standards create additional costs (for equipment manufacturers, operators and users), then why don't we observe an agreement on a single standard? Why the secession by Ericsson, Nokia and Siemens, which seems counter to the lock-in predicted by typical models of standards setting? One possible answer relies on the inefficiencies of negotiations among multiple players with possibly conflicting goals. In this paper, we argue that lack of standardization may be the natural outcome of competition even in a world with no inefficiencies in negotiations (Section 3); and may in fact be the socially optimal outcome (Section 4).

3 Model and equilibrium results

Consider an infinite horizon duopoly in an industry with an evolving technology. Specifically, suppose a technology can be at two different levels: 0

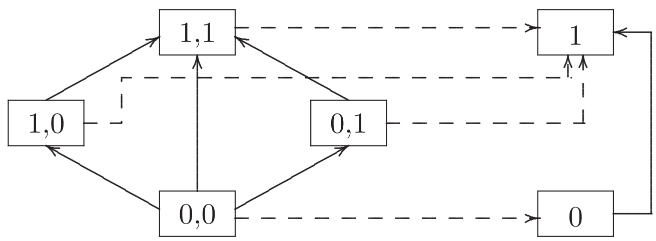

Figure 1: State space and transition paths. Solid arrows represent transitions by means of innovation outcomes. Dashed arrows represent transitions by means of standardization agreements.

and 1.[4] The horizon is divided into discrete periods, each of which is divided into three stages. In a first stage, firms decide whether to make their technology designs compatible.[5] In a second stage, firms independently make an R&D investment towards improving their technology. Specifically, in order to innovate with probability ρ a firm must spend $\frac{1}{2}\,\rho^2$.[6] Finally, in a third stage product market profits for the period are received.

Figure 1 summarizes the state space. Each rectangle represents a state. The definition of state includes information on whether a common standard has been agreed upon and the current technology level (levels, if an agreement has not be arrived at). States with two numbers (left-hand side of the figure) represent dual standard states; states with one number (right-hand side of the figure) represent single standard states. We denote by ${}_D(i,j)$ a state where no standardization has yet been achieved and technology levels are i and j; and by ${}_S(i)$ a state where a common standard has been achieved and its technology level is given by i. Since each period is divided into several stages, we must also indicate the stage within the period. The above notation, ${}_D(i,j)$ and ${}_S(i)$, refers to the beginning of each period (before standardization decisions have been made); for values *after* standardization decisions have been made we will use the notation ${}^+_D(i,j)$ and ${}^+_S(i)$.

In Figure 1, solid arrows represent transitions by means of innovation outcomes; and dashed arrows represent transitions by means of standardization agreements. Our assumptions regarding transition between states are

4. In terms of our wireless story, we can interpret level 0 as 2G and level 1 as 3G.
5. It is logically possible for one firm to make its technology design compatible with its rival, when the rival chooses not to. We will assume that the technologies will remain incompatible in this case.
6. Naturally, if a firm is at technology level 1 it will not spend any resources on innovation.

formalized as follows:

Assumption 1 *(a) Starting from state $_D(i,j)$, an improvement in firm i's technology leads to state $_D(i+1,j)$. (b) Starting from state $_S(i)$, an improvement in any firm's technology leads to state $_S(i+1)$. (c) Starting from state $_D(i,j)$, a standardization agreement leads to state $_S(\max\{i,j\})$.*

We thus consider two forms of state transitions. The first one is R&D, and it works according to Assumption 1 (a) and (b). The second form of state transition corresponds to standardization agreements, and it works according to Assumption 1 (c).[7] Notice that technology transitions take one period, whereas standardization agreements are nearly instantaneous in that they can be implemented between stages within a period. Moreover, we note that, implicit in Assumption 1, is the idea that standardization agreements are definitive, that is, should the firms agree to standardize in one period, then the firms continue to work with the same standard in subsequent periods, regardless of subsequent technological progress.

Our next assumptions relate to the profit functions. Let $\pi_D(i,j)$, $\pi_S(i)$ be the per-period product market profit functions at each possible state of standardization and technology level.

Assumption 2 *(a)* $\pi_S(i) > \pi_D(i,i),\ i=0,1$; *(b)* $2\,\pi_S(1) > \pi_D(1,0) + \pi_D(0,1)$.

Assumption 3 *(a)* $\pi_S(1) > \pi_S(0)$; *(b)* $\pi_D(1,0) > \pi_D(0,1)$.

Assumption 2 implies that, at every possible state, product market industry profits are greater with standardization than without. Assumption 3 reflects the fact that technology progress is good in terms of firm profits.

Next we turn to firm value functions, the discounted stream of profits along the equilibrium path (that is, assuming optimal decisions in the current and future periods). Let $V_D(i,j)$ and $V_S(i)$ be firm i's value function (in a state with dual and single standard, respectively) measured at the start of a period, that is, before standardization decisions have been made; and let $V_D^+(i,j)$ and $V_S^+(i)$ be the value functions measured after standardization decisions have been made. So, for example, if starting in

7. Notice that we only consider two levels of technology development. Therefore, Assumption 1 really only applies to $i=0$. Alternatively, we make the convention that state $_D(i,j)$ is equivalent to state $_D(1,j)$ when $i>1$ (and the same for $_S(i)$.)

state ${}_D(i,j)$ the firms agree on a common standard then, within the same period, we move from state ${}_D(i,j)$ (before standardization decisions take place) to state ${}^+_S(\max\{i,j\})$ (after standardization decisions take place).

Our next assumption relates to the nature of the standardization process. Whereas R&D effort choices are independently and non-cooperatively chosen, we assume the standardization process consists of a negotiation between the firms. Specifically, we assume efficient, equal-split bargaining:[8]

Assumption 4 *If standardization is efficient, that is, if* $2\,V^+_S(\max\{i,j\}) > V^+_D(i,j) + V^+_D(j,i)$*, then standardization takes place and the gains from standardization are equally split between the firms.*

Notice in particular that, if $2\,V^+_S(\max\{i,j\}) > V^+_D(i,j) + V^+_D(j,i)$, then $V_D(i,j) + V_D(j,i) = 2\,V^+_S(\max\{i,j\}) = 2\,V_S(\max\{i,j\})$.

Before proceeding, it is worthwhile restating our basic assumptions. A critical part of Assumption 1 is that standardization is an "absorbing" state. That is, once firms agree on a standard, then whatever improvements are achieved to that standard are shared by both firms, that is, both firms continue to own the common standard. This assumption plays a crucial role in our results. Assumptions 2 and 4 are made primarily for expositional purposes. In fact, they stack the cards in favor of standardization (bargaining is efficient, standardization increases product market profits). By making these assumptions, it is easier to understand the nature of our result, namely that standardization may not take place in equilibrium. Finally, Assumption 3 follows from the idea that technical progress improves firm value.

We will be looking for Markov equilibria of the above game, where strategies are a function of the state at which the game is. Our restriction to Markov equilibria excludes the possibility of time dependent strategies which would likely lead to multiple equilibria. As it happens, we show (by construction) that equilibrium is unique (among the set of Markov equilibria).

The main point of our paper is that standardization leads to a sort of free-riding problem, that is, an externality whereby the benefits from an individual firm's R&D effort accrue to both firms. As a result, in equilibrium and under some conditions firms prefer not to standardize.

Proposition 1 *Suppose that* $\pi_S(0) - \pi_D(0,0)$ *and* $\pi_D(1,0) - \pi_D(0,1)$ *are small. Then no standardization takes place in state* ${}_D(0,0)$*.*

8. To justify this, suppose that firms make alternating offers and that the time interval between offers is negligible. Rubenstein's (1982) result then implies our assumption.

An important step in the proof is to show that

$$V_D(1,0) > V_S(1) > V_D(0,1).$$

Even though (in equilibrium) state ${}_D(0,1)$ leads to state ${}_S(1)$, that is, firms agree on a common standard, the ex-ante payoff is greater for the firm that owns the superior technology. This is fairly intuitive: the outside option for a firm with a better technology is better. This in turn implies that each firm's innovation incentives when both firms are at technology level 0 differ according to whether the firms are investing in the same standard or in different standards.

Consider two alternative paths starting from state ${}_D(0,0)$. In case A, firms immediately agree on a common standard; in case B, firms only agree on a common standard in the next period (if by then we are still in state ${}_D(0,0)$). In other words, case B corresponds to a one-time deviation from case A. By the one-time deviation principle, in order to show that A is not an equilibrium, it suffices to show that firms would prefer to switch to B. This does not imply that a one-time deviation from A is an equilibrium, but it suffices to show that A is not an equilibrium.[9]

In case A, the net marginal return to R&D is given by

$$\delta\,(1-\widetilde{\rho})\Big[V_S(1) - V_S(0)\Big] - 1 \tag{1}$$

where $\widetilde{\rho}$ is the rival's level of R&D. This is intuitive: If the rival succeeds in R&D (probability $\widetilde{\rho}$) then our firm's R&D effort has no impact (since firms share a common standard). If the rival does not succeed in R&D (probability $1-\widetilde{\rho}$), then the marginal return to success is given by $\delta\,\Big[V_S(1) - V_S(0)\Big]$.

In case B, the net marginal return to R&D is given by

$$\delta\,(1-\widetilde{\rho})\Big[V_D(1,0) - V_S(0)\Big] + \delta\,\widetilde{\rho}\,\Big[V_S(1) - V_D(0,1)\Big] - 1$$

This is greater than the value in (1) for two reasons. First, if the rival does not succeed (probability $1-\widetilde{\rho}$), then we have $V_D(1,0) > V_S(1)$: although state ${}_D(1,0)$ immediately leads to ${}_S(1)$, a firm that begins negotiations with a superior technology gets more than one half of the value at stake. Second, if the rival does succeed (probability $\widetilde{\rho}$), then this firm still gains from R&D success: although the industry ultimately ends up at ${}_S(1)$ even if this firm

9. See for example Theorem 4.2 in Fudenberg and Tirole (1991).

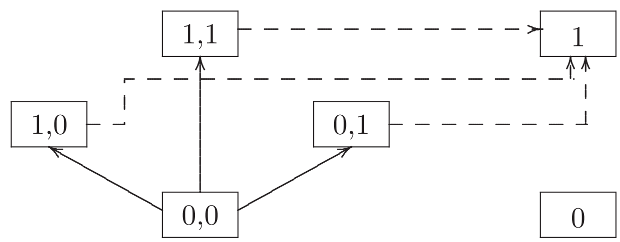

Figure 2: State space and transition paths observed along the equilibrium path (with positive probability).

does not succeed, it will benefit from having previously agreed to standardization, and will derive an equal, rather than smaller, share of the value.

The above intuition is fairly general, only requiring Assumptions 1–4. Why does then Proposition 1 require several parameter assumptions (which however are sufficient, not necessary conditions)? As mentioned above, standardization implies an externality: a benefit conferred on the rival firm. However, competitive R&D implies itself an externality: part of the gain obtained by firm i is gotten at the expense of firm j. Therefore, the fact that lack of standardization leads to higher levels of innovative effort does not necessarily imply that standardization is preferred by firms. Proposition 1 sets out a set of sufficient conditions such that the effect of a higher level of R&D leads firms to agree not to standardize. The assumption that $\pi_S(0) - \pi_D(0,0)$ is small implies that the short-term loss from lack of standardization is not too large, that is, short-run considerations are of secondary importance with respect to the level of R&D, that is. The assumption that $\pi_D(1,0) - \pi_D(0,1)$ is small implies that, under no standardization, the equilibrium level of R&D is not too large (from a joint-profit point of view); if that were the case, than lack of standardization would only magnify the distortion between private and collective optimum.

Figure 2 summarizes Proposition 1. Specifically, it shows all transitions that are observed along the equilibrium path with positive probability. Since the game starts from state ${}_D(0,0)$, we see that state ${}_S(0)$ is never visited. As soon as one of the firms achieves level 1, standardization ensues.

4 Social welfare

Proposition 1 is about positive analysis. It provides conditions under which standardization does not take place in state (0,0) even though firms' profits would be greater *in every state* if firms were to standardize. From the firms' point of view, the short-term losses from lack of standardization are more than compensated by longer-term benefits of higher levels of R&D expenditure. In fact, from each firm's point of view the equilibrium pattern of standardization is optimal.

In order to go from industry profits to social welfare we need a more detailed model of product market competition and consumer welfare. When consumer welfare and industry profits are relatively aligned regarding standardization decisions, Proposition 1 can be extended to state that no standardization at stage (0,0) is socially optimal. Whether this is true depends on the particular model of product market competition that applies. In what follows, we present a specific model that we believe reasonably reflects some of the features of wireless communications, and other types of technologies for which the interim costs of firms investing in different technologies is not too high.

Looking at the current situation of wireless communications in the U.S., we note that lack of standardization regarding the basic technology does not prevent consumers from benefiting from network effects: every consumer can communicate with every other consumer, regardless of which technology they are hooked up to. Lack of standardization can imply higher costs for sellers, who have to create means of hooking up networks based on different technologies. To the extent that these higher costs are reflected on prices, consumers are worse off. In other words, it seems fair to say that, when it comes to standardization, the main concern for consumers is prices rather than network effects.[10]

To be more specific, consider a Hotelling type duopoly where each firm is located at the extreme of a product variety segment and consumers are uniformly distributed along that segment (each consumer buys one unit from one of the sellers). If the sellers' technologies are not standardized, then both firms must incur higher fixed and marginal costs in order to provide consumers with universal network access. Let k_0, c_0 and k_1, c_1 be the sellers' fixed and marginal cost without and with standardization. Assume that $k_0 > k_1$ and $c_0 > c_1$. This is consistent with Assumption 2, namely that

10. A single standard, can, but need not, provide consumers with better coverage, especially during the roll-out phase. The anecdotal evidence contrasting the European and North American experiences, without controlling for differences in dates of spectrum allocations and population density, suggests that coverage was better in Europe. However, firms offering competing standards can have stronger incentives to compete in coverage than those offering the same technology.

industry profits are greater under standardization. Specifically, equilibrium firm profits are given by

$$\pi = \frac{1}{2}\,t - k_i \ \ (i = 1, 2),$$

whereas consumer surplus is given by

$$\mu = v - t - c_i \ \ (i = 1, 2),$$

where v is consumer valuation and t is the "transportation" cost.

Our main result in this section is that, if sellers' and buyers' incentives are properly aligned as regards the standardization decision, then the no-standardization equilibrium result from Proposition 1 can be extended to social welfare.

Proposition 2 *If $c_0 - c_1$ is sufficiently small, then if in equilibrium there is no standardization in state $(0, 0)$ it follows that no standardization is the socially optimal outcome in that state.*

5 Discussion

Our main result, Proposition 1, states that if the short run losses from lack of standardization are small and the profit difference between technology leader and technology laggard is also small, then in equilibrium firms prefer to follow different paths in their R&D efforts. What does this have to say regarding wireless telecommunications, the main motivating example we consider in this paper? We can think of second generation as our level zero technology and R&D as the effort to reach 3G. From a short run point of view, it might seem more efficient for Qualcomm and Nokia to agree on a common standard of 3G, that is, to move to state ${}_S(0)$. As it happened, the state remained at ${}_D(0, 0)$, with WCDMA and CDMA2000 representing each of the 0's. Many may lament this as an inefficient equilibrium resulting from inefficiencies in negotiations. We argue that, given the incompleteness of contracts involving IP, dual standards may have the benefit of maintaining research incentives that might otherwise be inefficiently diminished.

We take a somewhat extreme approach by assuming that, under standardization, all technology improvements are shared by the adherents to that standard; whereas, under dual standards, imitation is only possible under a standardization agreement. Reality is probably between these extremes.

But to the extent that standardization increases the free-riding problem of R&D effort, our qualitative result still holds. That is, our results hold as long as each competing firm has an incentive to develop new technologies faster than its rival. In this context, cooperative agreements and research joint ventures will solve the free riding problem, as such agreements will reduce investment incentives.

We consider a simple framework with two technology levels, 0 and 1. But before 3G there was 2G; and after 4G there will likely be 5G. We could consider a more general framework with an infinite technology ladder. Suppose that, in addition to standardization, firms may write license agreements. Our conjecture is that, each time a firm gets one step ahead of its rival, the laggard will license the technology from the leader but not necessarily follow the same standard for subsequent R&D efforts; whether these firms would do so can depend, as in the two technology level model, on the interim costs that are incurred when firms invest in different standards. We then reach state ${}_D(1,1)$, which effectively becomes the new state ${}_D(0,0)$. Technology licensing then has the benefits of (efficiently) bringing all firms to a higher technology level without imposing the free-riding inefficiencies of standardization.

Our assumptions regarding short-run profits purposely stack the cards in favor of standardization (that is, in each period, profits under a single standard are greater than under dual standards). The same is not necessarily true regarding our assumption of efficient negotiations. If negotiation costs are prohibitively high, then trivially there is no standardization agreement. However, intermediate levels of negotiations costs may or may not favor standardization. If the cost is uniform across all possible instances, then negotiations costs favor no standardization to the extent that they delay the cost from standard setting negotiations. Specifically, $V_S(0)$ is decreased by N, the negotiation cost, whereas $V_D(0,0)$ is decreased by $\delta\, N$, where δ is the discount factor. If N is large and δ small, this may switch the equilibrium from standardization to delayed standardization. However, it might be argued that the costs of reaching an agreement are higher when firms' technology levels are different than when they're equal. In that case, negotiations costs might favor early standardization. Specifically, $V_S(0)$ is decreased by N_S, whereas $V_D(0,0)$ is decreased by $(1-\rho^2)\, N_A + \rho^2\, N_S$, where N_S is the negotiation cost when both firms are at the same technology level and N_A is the negotiation cost when firms are at different technology levels. If the difference between N_S and N_A is sufficiently large, then the equilibrium may switch from delayed standardization to standardization in state $(0, 0)$.

6 Conclusion

Our analysis indicates that a regulatory policy mandating a single standard can, at times, be harmful, both from a consumer and from a social point of view. We provide a set of conditions such that, absent regulation, firms choose incompatible technologies. In this context, regulatory policy mandating compatible standards reduces investment incentives, retards innovation, and may ultimately reduce consumer and social welfare.

Our model suggests that the relation between standardization and innovation incentives is relatively robust. By contrast, the relation between a mandated standard and consumer welfare depends on various crucial parameters. If the consumer loss from multiple standards is sufficiently large, and if firm profits are not well aligned with consumer welfare, then a mandated standard may increase consumer welfare.

Finally, while our paper was motivated by the wireless telecommunications industry, we believe the problems we highlight are of more general importance. For example, the EU recently decided on a standard for mobile TV. On March 17, 2008, Viviane Reding, EU Commissioner for the Information Society and Media, stated that

> For Mobile TV to take off in Europe, there must first be certainty about the technology. This is why I am glad that with today's decision, taken by the Commission in close coordination with the Member States and the European Parliament, the EU endorse DVB-H as the preferred technology for terrestrial mobile broadcasting.[11]

While we cannot claim the EU's decision to be right or wrong in the present context, we challenge the assertion that a mandated standard is in general the best solution.

11. See http://europa.eu/rapid/pressReleasesAction.do?reference=IP/08/451&format=HTML&aged=0&language=EN&guiLanguage=en, visited on April 7, 2008.

Appendix

Proof of Proposition 1: The proof proceeds as follows. We assume that the equilibrium is for firms to standardize at all states and then show that, by not standardizing at state (0,0), firm payoffs increases. We do so in four steps. In Step 1 we show that, whenever one of the firms has achieved technology level 1, a subgame perfect equilibrium implies that firms agree on a standard. Given this, we focus on state (0,0), the crucial state for our analysis. In Step 2, we consider the possibility of, contrary to equilibrium prescription, the firms *not* agreeing on a common standard. We argue that this leads to a higher level of investment in R&D at state ${}_D(0,0)$ if and only if $V_D(1,0)$ is greater than $V_S(1)$. In Step 3, we show that, as $\pi_D(0,1) - \pi_D(1,0) \to 0$, $\rho_D(0,1) \to 0$ and $V_D(1,0)$ converges to $V_S(1)$ from above. Together with Step 3, this implies that R&D investment increases when firms fail to agree on a common standard. Finally, in Step 4 we show that the increase in R&D leads to an increase in firm value, thus proving that there can be no standardization in equilibrium in state (0,0).

□ **Step 1.** Suppose first we are in state ${}_D(1,1)$, that is, both firms are at technology level 1 and each has its own standard. If firms do not agree on a common standard, then product market profits are $\pi_D(1,1)$ for each. If they agree on a common standard, then product market profits are $\pi_S(1)$ for each. Assumption 2 then implies that at state ${}_D(1,1)$ firms agree on a common standard. In fact, there is no additional R&D and so product market profits is all that matters; and, by assumption, we have efficient bargaining, which leads to the efficient solution (from the firms' perspective). We thus have

$$V_D(1,1) = V_S(1) = \frac{\pi_S(1)}{1-\delta}, \tag{2}$$

where δ is the discount factor.

Suppose now we are in state ${}_D(1,0)$. Since firms can achieve the same industry payoffs as in state ${}_S(1)$, and given Assumptions 3–4, we conclude that firms choose standardization. We thus have $V_D(0,1) + V_D(1,0) = 2\,V_S(1)$. The exact split of the pie $2\,V_S(1)$ depends on the outside option for each firm, which we consider below.

□ **Step 2.** As mentioned earlier, our starting point is the hypothesis that there exists an equilibrium where firms agree on a common standard at every state ${}_D(i,j)$. In state ${}_S(0)$, each firm chooses ρ to maximize

$$\delta\Big[(1-\rho)\,(1-\widetilde{\rho})\,V_S(0)+(\rho+\widetilde{\rho}-\rho\,\widetilde{\rho})\,V_S(1)\Big]-\frac{1}{2}\,\rho^2 \tag{3}$$

where $\widetilde{\rho}$ is the rival's choice of ρ. This is a concave function of ρ. Solving the first-order condition and imposing the symmetry condition $\widetilde{\rho}=\rho$, we get

$$\rho_S(0)=\frac{\delta\Big(V_S(1)-V_S(0)\Big)}{1+\delta\Big(V_S(1)-V_S(0)\Big)} \tag{4}$$

Now consider a one-time deviation whereby firms do not agree on a standard at ${}_D(0,0)$. By the one-stage deviation principle, a necessary condition for standardization to be an equilibrium is that payoffs be no higher under no standardization during one period.[12] Let $\overset{\circ}{{}_D}(0,0)$ be the state corresponding to this one-stage deviation. In this state, each firm chooses ρ to maximize

$$\delta\Big[(1-\rho)\,(1-\widetilde{\rho})\,V_D(0,0)+\rho\,(1-\widetilde{\rho})\,V_D(1,0)+ \\ (1-\rho)\,\widetilde{\rho}\,V_D(0,1)+\rho\,\widetilde{\rho}\,V_D(1,1)\Big]-\frac{1}{2}\,\rho^2$$

Notice that, if none of the firms succeeds, then we move to state $(0,0)$ and standardization takes place, implying that $V_D(0,0)=V_S(0)$. This is the essence of the one-stage deviation exercise. Moreover, by subgame perfection and (2), $V_D(1,1)=V_S(1)$. Solving the first-order condition and imposing the symmetry condition $\widetilde{\rho}=\rho$, we get

$$\rho_D^{\circ}(0,0)=\frac{\delta\Big[V_D(1,0)-V_S(0)\Big]}{1+\delta\Big[V_D(1,0)-V_S(0)-V_S(1)+V_D(0,1)\Big]}$$

Efficient bargaining implies that $V_D(0,1)+V_D(1,0)=2\,V_S(1)$. We thus have

$$\rho_D^{\circ}(0,0)=\frac{\delta\Big[V_D(1,0)-V_S(0)\Big]}{1+\delta\Big[V_S(1)-V_S(0)\Big]} \tag{5}$$

By comparing (4) and (5), we conclude that $\rho_D^{\circ}(0,0)>\rho_S(0)$ if and only if $V_D(1,0)>V_S(1)$.

12. See for example Theorem 4.2 in Fudenberg and Tirole (1991).

□ **Step 3.** We now prove that, as $\pi_D(0,1) - \pi_D(1,0) \to 0$, $\rho_D(0,1) \to 0$ and $V_D(1,0)$ converges to $V_S(1)$ from above.

Let $V_D^+(0,1)$ and $V_D^+(1,0)$ denote the value function, measured *after* standardization decisions have been made but *before* R&D investments have been made, corresponding to a one-time deviation from the equilibrium path whereby firms do *not* agree on a common standard. That is, $V_D^+(0,1)$ corresponds to the outside option in the standardization negotiations that take place in state $(1,0)$, in which the firm with technology level 0 does not license the new technology from the other firm. Note that the firm with technology at level 1 chooses zero investment in R&D (since it cannot possibly move any further up in technology level and R&D is costly). We then have

$$\widetilde{V}_D^+(0,1) = \pi_D(0,1) + \delta \left(\rho \, \frac{\pi_S(1)}{1-\delta} + (1-\rho)\, V_D(0,1) \right) - \frac{1}{2}\,\rho^2 \tag{6}$$

$$V_D^+(1,0) = \pi_D(1,0) + \delta \left(\rho \, \frac{\pi_S(1)}{1-\delta} + (1-\rho)\, V_D(1,0) \right) \tag{7}$$

where the value of $\rho = \rho_D(0,1)$ is given by

$$\rho_D(0,1) = \arg\max_{\rho} \left\{ \delta \left(\rho \, \frac{\pi_S(1)}{1-\delta} + (1-\rho)\, V_D(0,1) \right) - \frac{1}{2}\,\rho^2 \right\} \tag{8}$$

We are now ready to analyze the negotiation game at stage $_D(0,1)$. If there is standardization, then each firm gets $V_S^+(1) = V_S(1)$. If negotiations break down, then firms get $V_D^+(0,1)$ and $V_D^+(1,0)$. We then have

$$\begin{aligned} V_D(0,1) + V_D(1,0) &= 2\,V_S(1) \\ V_D(0,1) - V_D^+(0,1) &= V_D(1,0) - V_D^+(1,0) \end{aligned}$$

The first equation follows from Assumption 2 (standardization increases joint profits) and from Assumption 4 (efficient bargaining). The second equation states that the gains from standardization are equally split between the two firms (again by Assumption 4).

Solving the above system of equations, we get

$$\begin{aligned} V_D(0,1) &= V_S(1) - \frac{1}{2}\,\Delta \\ V_D(1,0) &= V_S(1) + \frac{1}{2}\,\Delta. \end{aligned} \tag{9}$$

where

$$\Delta \equiv V_D^+(1,0) - V_D^+(0,1)$$

Subtracting (6) from (7) and simplifying, we get

$$\Delta = [1 - \delta (1 - \rho)]^{-1} \Big(\pi_D(1,0) - \pi_D(0,1) + \frac{1}{2} \rho^2 \Big) > 0 \qquad (10)$$

where the inequality follows from part (b) of Assumption 3. Together with (9), this implies that

$$V_D(1,0) > V_S(1) > V_D(0,1). \qquad (11)$$

Substituting (9) into (8), imposing $\pi_D(0,1) = \pi_D(1,0)$, and simplifying we get

$$\rho_D(0,1) = \arg\max_{\rho} \left\{ k - \frac{(1-\delta)\,\rho^2}{2\,\big(1-\delta\,(1-\rho)\big)} \right\}$$

where $k \equiv \frac{\delta}{1-\delta}\,\pi_S(1)$ is independent of ρ. Since $\delta \in (0,1)$, the term in curly brackets is decreasing in ρ. Since all the relevant functions are continuous, it follows that $\rho_D(0,1) \to 0$ as $\pi_D(0,1) - \pi_D(1,0) \to 0$. Given that $\rho_D(0,1) \to 0$, it follows from (10) that $\Delta \to 0$, and from (9) that $V_D(0,1) - V_S(1) \uparrow 0$ and $V_D(1,0) - V_S(1) \downarrow 0$.

Intuitively, if $\pi_D(0,1) \approx \pi_D(1,0)$, then firm 0 knows that, as long as we remain in the current state, both firms make approximately the same profit. This means the outside option is the same for both firms. This means that they should split the gains from standardization. This in turn implies that firm 0 should expect to get $V_S(1)$. But this is what firm 0 gets from succeeding in its own R&D effort. Since R&D is costly, firm 0 is better off by not investing at all.

□ **Step 4.** Suppose that, at state $_S(0)$, both firms were to increase ρ by the same amount starting from the equilibrium level $\rho_S(0)$. Setting $\widetilde{\rho} = \rho$ in (3) and differentiating with respect to ρ, we get

$$\frac{dV_S(0)}{d\rho} = \delta\, 2\,(1-\rho) \Big[V_S(1) - V_S(0) \Big] - \rho$$

Substituting (4) for ρ, and simplifying, we get

$$\left.\frac{dV_S(0)}{d\rho}\right|_{\rho=\rho_S(0)} = \rho_S(0) > 0$$

It follows that firm value at state (0,0) increases if both firm's R&D investment increases by a small amount. But if $\pi_D(0,1) \approx \pi_D(1,0)$ and firms do not agree on a standard at (0,0) then R&D investment increases by a small amount. Finally, if $\pi_S(0) - \pi_D(0,0)$ is sufficiently close to zero then the effect of increasing ρ dominates the short-term loss in profits. ■

Proof of Proposition 2: If $c_1 - c_0$ is sufficiently close to zero, then most of the cost of providing connection under no standardization is borne out by sellers. Since we assume efficient bargaining between sellers, the equilibrium outcome is optimal from the sellers' point of view, which in turn is a sufficient condition for it to be better from a social point of view. ■

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