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Evolving technologies and standards regulation☆

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ABSTRACT

The EU mandated a single standard for second generation wireless telecommunications, whereas the US allowed several incompatible standards to battle for market share. Motivated by this example, 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.

1. Introduction

Spectrum regulation necessarily involves regulation of the technology that licensees can use. Beginning in the early 1990s, the US Federal Communications Commission (FCC), as well as regulatory agencies in other countries started taking 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 emission restrictions. At one point there were four 2G technologies with virtually nationwide coverage in the US.

In contrast with the US approach, the European Union (EU) 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 have taken a similar approach towards 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 provides unambiguous support for it. The purpose of this paper is to formally examine the claim that standards regulation — specifically, the encouragement or enforcement of a standard — 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

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their own standard. We also provide conditions such that a non-standardization equilibrium is socially optimal.

1.1. Related literature

Several authors have dealt with the economic analysis of standard setting. Katz and Shapiro (1985), Farrell and Saloner (1985, 1988) and Arthur (1989) laid down some of the theoretical groundwork on the problem of technology choice and standardization.[1] Recent papers have looked more closely at the actual process of standard setting, both from a theoretical and form an empirical perspective: Chiao et al. (2007), Leiponen (2008), Simcoe (2012), Farrell and Simcoe (2012). Since our focus is on the choice of whether or not to set a standard, we do not focus on the details of the standardization process, rather we assume a rather simple standardization process. In fact, since we want to highlight the strategic value of non-standardization, we "stack the cards" in favor of standardization by assuming a frictionless process of standard setting.

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-poststandardization 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.

Erkal 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).

Much of the literature on network effects and standards (e.g., Arthur, 1989), has emphasized the phenomena of tipping and de facto standardization. However, the real world is full of examples when standardization does not occur despite the presence of significant network effects. The economics literature has explained this as the result of multi-homing (e.g., Corts and Lederman, 2009), dynamic pricing (Cabral, 2011; Mitchell and Skrzypacz, 2006), or competition between complementary goods providers (Church and Gandal, 1993; Ellison and Fudenberg, 2003; Kretschmer, 2008). Greenstein and Rysman (2007), for example, show that, in the case of 56K modem standards, participants "knew" in advance that there would ultimately be a single standard dictated by the ITU but engaged in standards competition anyway. They explain the outcome as an instance of the "complementary goods provider" case. Our paper offers a new explanation for why early standardization might not occur as it did not.

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, now in its fourth generation. 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 et al., 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.

The European Union delegated standard setting to the European Technical Standards Institute (ETSI), which mandated GSM. In contrast, the FCC in the US 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 (Cabral and Kretschmer, 2006; Gandal et al., 2003). 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 US, 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 and Ameritech, among others; note that, except for Sprint, all of these are now part of Verizon Wireless).

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.

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. In addition, 2G CDMA operators can easily upgrade to CDMA2000, merely by replacing some radio equipment at base stations and upgrading the software operating 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.

Similarly to second generation wireless standards, virtually all European operators deployed WCDMA. In the US, both CDMA2000 and WCDMA were deployed: ATT and T-Mobile opted for WCDMA, while the other two nationwide operators chose CDMA2000.[2]

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 US 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 US. 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

[1] See David and Greenstein (1990) for a survey of this early literature.

[2] Most countries outside of the Western Hemisphere adopted the European standards, whereas most of the Americas followed US adoption patterns. China deployed both WCDMA and CDMA2000, while India only released a very limited amount of 3G spectrum in 2010.

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.

Since 2010, a fourth generation of wireless technologies has been deployed. Mostly, this has been a frequency division version of the Long Term Evolution (LTE) standard.[3] Many of the patterns present in earlier generations of wireless technology also seem to be present in the ongoing phase.

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

Fig. 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 been 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 (i, j) a state where no standardization has yet been achieved and technology levels are i and j; and by (i) a state where a common standard has been achieved and its technology level is given by i. Since each period is divided into two stages, we must also indicate the stage within the period. In fact, within the same period of time it is possible that we are at two different stages. Suppose, for example, that we start at the beginning of the period in state $(0, 0)$. Suppose moreover that firms agree on a common standard. Then we move to state (0). In fact, during the second stage of the current period, when profits are received and innovation decisions made, the relevant state is given by (0). Normally, the context indicates whether we refer to the first or the second stage within a period. When that is not the case, we will indicate explicitly what combination of state and stage we refer to.

Since states are determined by the number of standards and the technology level of each standard, there are two ways to move from one state to another.

In Fig. 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 formalized as follows:

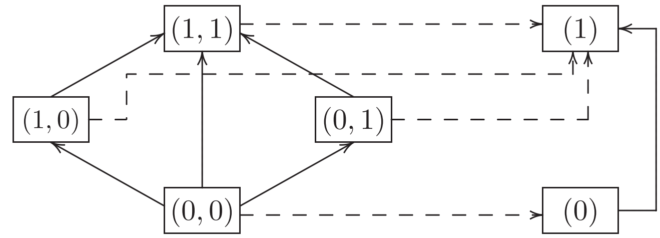

Fig. 1. State space and transition paths. Solid arrows represent transitions by means of innovation outcomes. Dashed arrows represent transitions by means of standardization agreements.

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

The first type of state transitions, resulting from innovation, takes place according to Assumption 1 (a) and (b). The second type of state transition, resulting from standardization agreements, takes place 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 $\pi(i,j)$, $\pi(i)$ be the per-period product market profit functions at each possible state of standardization and technology level.

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

Assumption 3. (a) $\pi(1) > \pi(0)$; (b) $\pi(1,0) > \pi(0,1)$.

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 $V(i, j)$ and $V(i)$ be firm i's value function (in a state with a dual and a single standard, respectively) measured at the start of a period, that is, before standardization decisions have been made, and let $V^+(i,j)$ and $V^+(i)$ be the value functions measured after standardization decisions have been made. So, for example, if starting in state (i, j) the firms agree on a common standard then, within the same period, we move from state (i, j) (before standardization decisions take place) to state $(\max\{i,j\})$ (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. This assumption is consistent with an alternating-offers bargaining game in which the time interval between offers is negligible (see Rubinstein, 1982).

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

[3] However, ATT has termed their HSPA+ standard 4G, although it is a variant of 3G. And there is a Time Division version of LTE that has been deployed in China and India.

[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.

[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 (i, j) is equivalent to state $(1, j)$ when $i > 1$ (and the same for (i).)

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

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 subgame-perfect Markov equilibria of the above game, where strategies are a function of the state of the game. Strictly speaking, the game we consider is a biform game, since it includes both cooperative and non-cooperative game theoretic elements (Brandenburger and Stuart, 2007). The non-cooperative element is that firms agree on common standard when there is a joint benefit from doing so. The non-cooperative element corresponds to the choice of R&D level. 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 as a second-best solution to the free-riding problem.

Proposition 1. *There exists an $\epsilon > 0$ such that, if $\pi(1{,}0) - \pi(0{,}1) < \epsilon$ and $\pi(0) - \pi(0{,}0) < \epsilon^2$, then no standardization takes place in state (0, 0).*

The complete proof of Proposition 1 may be found in Appendix A. An important step in the proof is to show that

$$V(1,0) > V(1) > V(0,1).$$

Even though (in equilibrium) state (0, 1) leads to state (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.

Specifically, consider two alternative paths starting from state (0, 0). In case A, firms immediately agree on a common standard; in case B, firms only agree on a common standard once one of them has innovated. In case A, the net marginal return to R&D is given by

$$\delta(1-\tilde{\rho})(V(1)-V(0))-1 \tag{1}$$

where $\tilde{\rho}$ is the rival's level of R&D. This is intuitive: If the rival succeeds in R&D (probability $\tilde{\rho}$) 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 $1-\tilde{\rho}$), then the marginal return to success is given by $\delta(V(1) - V(0))$.

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

$$\delta(1-\tilde{\rho})(V(1,0)-V(0,0)) + \delta\tilde{\rho}(V(1)-V(0,1))-1.$$

In the proof, we show that this value is greater than the value in (1). If the rival does not succeed (probability $1-\tilde{\rho}$), then the advantage of no standardization at (0, 0) (from an innovation incentive point of view) is that the payoff from innovation is given by $V(1,0)$, which is greater than $V(1)$: although state (1, 0) immediately leads to (1), a firm that begins negotiations with a superior technology gets more than one half of the value at stake. Moreover, even if the rival does succeed in R&D (probability $\tilde{\rho}$), there is still a positive incentive to do R&D, whereas under standardization the marginal benefit would be zero. The reason is that, although state (0, 1) immediately leads to (1), a firm that begins negotiations with an inferior technology gets less than one half of the value at stake.

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 provides 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 $\pi(0) - \pi(0{,}0)$ 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. The assumption that $\pi(1{,}0) - \pi(0{,}1)$ 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.

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

Note that, in equilibrium, the (symmetric) level of R&D is always strictly between 0 and 1.[8] This implies that the equilibrium path leads to technology progress with probability 1 in finite time, at which point standardization takes place. In other words, the proposition states that there is no standardization at state (0, 0), a state which in equilibrium is only visited for a finite number of periods. In this sense, it's a result about *delayed* standardization rather than *no* standardization.

3.1. Numerical simulations

Proposition 1 is only valid for a specific set of parameter values. How frequent is the outcome of no standardization at state (0, 0)? In order to address this question, we next consider some numerical simulations. In order to better understand the effect of the various parameter values, we consider the following model parameterization:

$$\begin{aligned}
\pi(1,1) &= \pi(0,0)\ (1+\gamma)\\
\pi(0) &= \pi(0,0)\ (1+\mu)\\
\pi(1) &= \pi(1,1)\ (1+\mu)\\
\pi(1,0) &= \pi(1,1)\ (1+\nu)\\
\pi(0,1) &= \pi(1,1)\ (1-\nu).
\end{aligned}$$

In words, γ measures the degree of technical progress (percent increase in profits) as we shift from technology level 0 to technology level 1; μ measures the percent increase in firm profits provided by a common standard, starting from a situation when both firms hold standards at the same technological level; and ν measures the increase (resp. decrease) in profits when a given firm (resp. the rival) has a better standard in a situation of dual standards.

With this payoff structure, the model is completely parameterized by $\pi(0{,}0)$, δ as well as the three-fold (γ,μ,ν). Fig. 3 considers the case

[8] The intuition for $\rho > 0$ is that the marginal cost of R&D is very low for low values of R&D; and Assumptions 1–4 imply that the gains from successful R&D are bounded away from zero. The intuition for $\rho < 1$ is not as obvious. There may be *asymmetric* corner solutions. However, if both firms choose the same level of R&D, then it must be $\rho < 1$. In fact, if the rival firm were to chose $\rho = 1$, then my net marginal benefit from R&D at $\rho = 1$ would be negative.

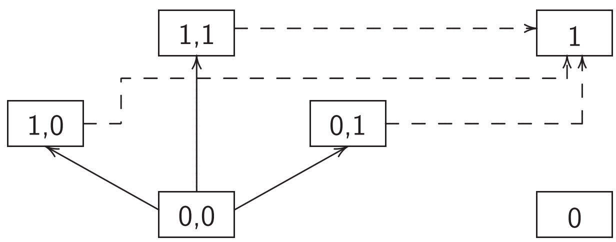

Fig. 2. State space and transition paths observed along the equilibrium path (with positive probability).

when $\pi(0,0) = .1$, $\delta = .9$, and $\gamma = 9$. This corresponds to the case of a very drastic innovation, that is, a ten-fold increase in firm profits as a result of technical progress. The axis in Fig. 3 corresponds to the degree of competitive advantage from a superior standard (ν, horizontal axis), and the static benefits from standardization (μ, vertical axis).

The dark-shaded area denotes the case when the equilibrium consists of dual standards being kept in state (0, 0), that is, the equilibrium when standardization only takes place after technology progress takes place. Not surprisingly, if the static benefits from standardization are sufficiently high (high μ) then in equilibrium firms prefer to agree on a common standard at all states, including (0, 0).

In Fig. 3 we consider a fairly drastic rate of technical progress. What if the value of γ is equal to 1 instead of 9; that is, what if profits are doubled instead of multiplied by 10? Fig. 4 considers this alternative situation. The qualitative nature of Fig. 4 is similar to that of Fig. 3. However, the area where the equilibrium corresponds to dual standards at (0, 0) is now smaller. This is intuitive: the main benefit from dual standards at (0, 0) — that is, delayed standardization — is to create greater innovation incentives; and the greater the rate of technical progress, the greater the benefit from increasing innovation incentives.

Figs. 3 and 4 suggest that the greater the value of ν (the competitive advantage from having a better standard than the rival), the more likely a dual standard equilibrium. In fact, a higher ν implies a greater innovation incentive, and the free-riding problem implies that standardization leads to too little innovation. However, this is an incomplete characterization of the relevant effects. Consider Fig. 5 where we compute equilibrium values for an even lower value of γ, .2. As can be seen, the boundary between standardization and dual-standard equilibrium may be non-monotonic: there exist values of μ such that, as we increase ν, the equilibrium involves one standard, then two standards, then one standard again.

Intuitively, a very high ν may lead to an excessively high value of innovation efforts. Specifically, a high ν together with a low γ implies that most of the innovation benefit is a relative benefit, that is, a relative benefit for the innovating firm and a cost for the non-innovating firm. Innovation then becomes a sort of rent-seeking game, which as is well known may end in excessive competition and lower equilibrium payoff.

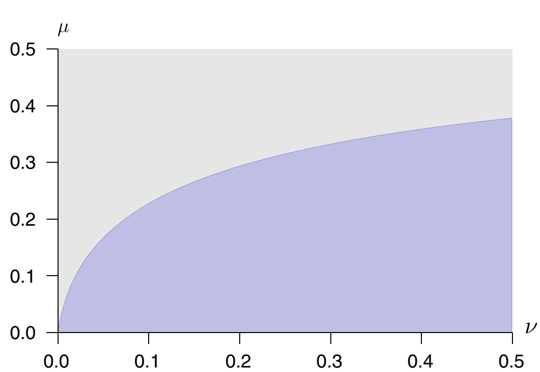

Fig. 3. The dark shaded area indicates that dual standards lead to higher firm value than a single standard. In this simulation, $\delta = .9$, $\pi(0,0) = .1$, $\pi(1,1) = 1$.

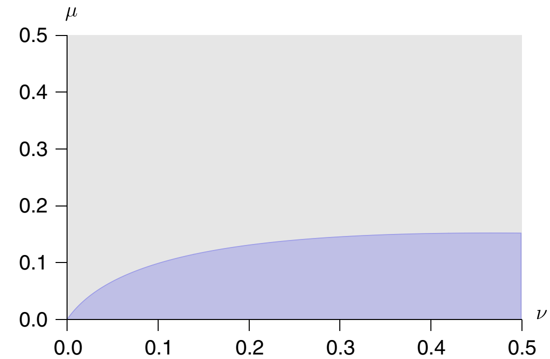

Fig. 4. The dark shaded area indicates that dual standards lead to higher firm value than a single standard. In this simulation, $\delta = .9$, $\pi(0,0) = .1$, $\pi(1,1) = .2$.

Finally, notice that the above numerical simulations confirm Proposition 1. In fact, the conditions $\pi(1,0) - \pi(0,1) < \epsilon$ and $\pi(0) - \pi(0,0) < \epsilon^2$ are equivalent to the conditions $\nu < \epsilon$ and $\mu < \epsilon^2$. In terms of Figs. 3–5, this corresponds to a point close to the origin and relatively closer to the horizontal axis. As can be seen, this always corresponds to a point in the shaded area, where the equilibrium consists of no standardization at state (0, 0).

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 reflects some of the features of wireless communications reasonably, as well as the features of other industries 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 US, 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 in 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.[9]

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

[9] 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.

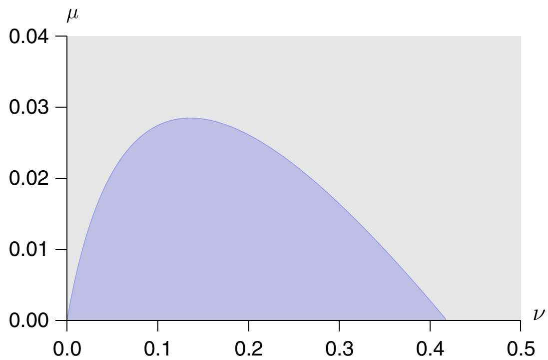

Fig. 5. The dark shaded area indicates that dual standards lead to higher firm value than a single standard. In this simulation, $\delta = .9$, $\pi(0,0) = .1$, $\pi(1,1) = .12$.

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, respectively. Assume that $k_0 > k_1$ and $c_0 > c_1$. This is consistent with Assumption 2, namely that industry profits are greater under standardization. Specifically, equilibrium firm profits are given by

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

Note that, since marginal cost is the same for both firms, equilibrium profits do not depend on marginal cost; all changes in marginal cost are passed on to consumers. In fact, 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. *There exists an $\epsilon > 0$ such that, if $c_0 - c_1 < \epsilon$, and if in equilibrium there is no standardization in state (0,0), then 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 3G as the level 1 technology.[10] Essentially, two designs were proposed: Qualcomm's CDMA2000 and WCDMA, the design favored by Nokia, Ericsson and a few others.

From a short run point of view, it might seem more efficient for the main proponents of the different 3G standards to agree on a common 3G standard, that is, to move to state (0) in Fig. 1. This would imply that all firms would converge their 2G standards into a common 2G standard and then work on improving it to 3G. As it happened, the state remained at (0, 0), with CDMAOne and GSM representing each of the 0's. Moreover, two distinct 3G standards were developed, CDMA2000 and WCDMA, representing state (1, 1).

Differently from our model's prediction, the industry did not converge so quickly on a common 3G standard, that is, state 1. Our analysis of the welfare benefits of competing standards is probably overstated for this reason. However, we should remember that we artificially limited the number of states to 0 and 1. A more complicated model, where 4G would correspond to state 2, might very well imply an equilibrium where no standardization takes place in state (1, 1), for the same reason that standardization does not take place in state (0, 0) of a two period model.

Many may lament the lack of standardization 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.

We consider a simple framework with two technology levels, 0 and 1. But before 3G there was 2G, after 3G there was 4G, and 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-level model, on the interim costs that are incurred when firms invest in different standards. The idea is that technology licensing then has the benefits of (efficiently) bringing all firms to a higher technology level without imposing the free-riding inefficiencies of standardization.

6. Conclusion

We provide a set of conditions such that, in the absence of 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 that the problems we highlight are of more general importance. For example, a few years after deciding on a single 3G standard, the EU faced a similar decision for 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.

[10] We could also start with 3G as the level 0 technology and 4G as level 1.

[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 A

Proof of Proposition 1. The proof proceeds as follows. We compute two equilibrium candidates: one in which firms standardize at all states, one where firms standardize at all states but (0, 0). We show that by not standardizing at state (0, 0), firm payoffs are higher, which in turn implies the result. We do so in five steps. In Step 1 we show that, whenever one of the firms achieves technology level 1, subgame perfection 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 an equilibrium where firms achieve a common standard at all states. In Step 3, we consider an alternative equilibrium candidate where firms standardize at all states but (0, 0). In Step 4, we show that, as $\pi(0,1) - \pi(1,0) \to 0$, then $\rho(0,1) \to 0$ and $V(1,0)$ converges to $V(1)$ from above. Finally, in Step 5 we show that the equilibrium without standardization at (0, 0) leads to a higher ρ and a higher $V(0,0)$ then the equilibrium with standardization. Specifically, we show that, starting from an equilibrium with standardization in every state, a switch to no standardization in state (0, 0) leads to a higher level of ρ during that period, and such increase in ρ leads to a higher equilibrium firm value.

□ **Step 1.** Suppose first we are in state (1, 1) and at the beginning of the period, 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 $\pi(1,1)$ for each. If they agree on a common standard, then product market profits are $\pi(1)$ for each. Assumption 2 then implies that at state (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

$$V(1,1) = V(1) = \frac{\pi(1)}{1-\delta}, \tag{2}$$

where δ is the discount factor.

Suppose now we are in state (1, 0). Since firms can achieve the same industry payoffs as in state (1), and given Assumptions 3–4, we conclude that firms choose standardization. We thus have

$$V(0,1) + V(1,0) = 2\,V(1). \tag{3}$$

The exact split of the pie $2V(1)$ depends on the outside option for each firm, which we consider below.

We next compare two possible equilibrium candidates, one where standardization takes place at (0, 0), one where it does not.

□ **Step 2.** Suppose first that there exists an equilibrium where firms agree on a common standard at every state (i, j), including (0, 0). The value $V(0, 0)$ is then given by

$$V(0,0) = \pi(0) + \delta\Big((1-\rho)^2\ V(0) + \Big(1-(1-\rho)^2\Big)V(1)\Big) - \frac{1}{2}\ \rho^2 \tag{4}$$

where $\rho = \rho(0)$ is the (symmetric) equilibrium value of ρ at (0). Given our equilibrium assumption, we have $V(0,0) = V(0)$. We can therefore solve Eq. (5) to get

$$V(0,0) = \frac{\pi(0) + \delta\Big(1-(1-\rho)^2\Big)V(1) - \frac{1}{2}\rho^2}{1-\delta\ (1-\rho)^2} \tag{5}$$

where again $\rho = \rho(0)$. We now determine this equilibrium value of ρ. In state (0), each firm chooses ρ to maximize

$$\delta\Big((1-\rho)\ (1-\tilde{\rho})\ V(0) + (\rho + \tilde{\rho} - \rho\,\tilde{\rho})\ V(1)\Big) - \frac{1}{2}\ \rho^2 \tag{6}$$

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

$$\rho(0) = \frac{\delta(V(1) - V(0))}{1 + \delta(V(1) - V(0))}. \tag{7}$$

Note that, insofar as $V(0)$ depends on $\rho(0)$, the above equation does not provide an explicit expression for $\rho(0)$. However, for the purposes of the proof, it suffices to write $\rho(0)$ as such.

□ **Step 3.** Now consider an alternative equilibrium candidate whereby firms never agree on a standard at (0, 0). The value $V(0, 0)$ is then given by

$$V(0,0) = \pi(0,0) + \delta\Big((1-\rho)^2\ V(0,0) + \Big(1-(1-\rho)^2\Big)V(1)\Big) - \frac{1}{2}\ \rho^2 \tag{8}$$

where $\rho = \rho(0,0)$ is the (symmetric) equilibrium value of ρ at (0, 0). In writing this expression we use the fact that, by Eq. (3), conditional on *any* firm succeeding in R&D, average continuation payoff is $V(1)$. Solving Eq. (8) for $V(0, 0)$, we get

$$V(0,0) = \frac{\pi(0,0) + \delta\Big(1-(1-\rho)^2\Big)V(1) - \frac{1}{2}\rho^2}{1-\delta\ (1-\rho)^2}. \tag{9}$$

In state (0, 0), each firm chooses ρ to maximize

$$\delta\Big((1-\rho)\ (1-\tilde{\rho})\ V(0,0) + \rho\ (1-\tilde{\rho})\ V(1,0) + (1-\rho)\ \tilde{\rho}\ V(0,1) + \rho\tilde{\rho}\ V(1,1)\Big) - \frac{1}{2}\ \rho^2$$

where $\tilde{\rho}$ is the rival's choice of ρ. Maximizing with respect to ρ and using Eqs. (2) and (3), and then imposing the symmetry condition $\tilde{\rho} = \rho$, we get

$$\rho(0,0) = \frac{\delta(V(1,0) - V(0,0))}{1 + \delta(V(1) - V(0,0))}. \tag{10}$$

Notice that the expressions for $V(0, 0)$ in the two candidate equilibria, Eqs. (5) and (8), are identical except that the values of ρ are different: $\rho = \rho(0)$, given by Eq. (7), when there is a common standard; and $\rho = \rho(0,0)$, given by Eq. (10), when no common standard is agreed to at state (0, 0). In the next two steps we will show that ρ is higher under the no-standardization equilibrium (Step 4) and that a higher value of ρ is associated with a higher value of $V(0, 0)$ (Step 5), which concludes the proof that no standardization takes place in equilibrium in state (0, 0).

□ **Step 4.** We now prove that, as $\pi(0,1) - \pi(1,0) \to 0$, $\rho(0,1) \to 0$ and $V(1, 0)$ converges to $V(1)$ from above.

Let $V^+(0,1)$ and $V^+(1,0)$ 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, $V^+(0,1)$ 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

$$V^+(0,1) = \pi(0,1) + \delta\left(\rho\frac{\pi(1)}{1-\delta} + (1-\rho)V(0,1)\right) - \frac{1}{2}\rho^2 \tag{11}$$

$$V^{+}(1,0)=\pi(1,0)+\delta\left(\rho\frac{\pi(1)}{1-\delta}+(1-\rho)V(1,0)\right) \tag{12}$$

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

$$\rho(0,1)=\underset{\rho}{arg\,max}\left\{\delta\left(\rho\frac{\pi(1)}{1-\delta}+(1-\rho)V(0,1)\right)-\frac{1}{2}\rho^2\right\}. \tag{13}$$

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

$$V(0,1)+V(1,0)=2\,V(1)$$
$$V(0,1)-V^{+}(0,1)=V(1,0)-V^{+}(1,0).$$

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

$$\begin{aligned}V(0,1)&=V(1)-\frac{1}{2}\Delta\\ V(1,0)&=V(1)+\frac{1}{2}\Delta\end{aligned} \tag{14}$$

where

$$\Delta\equiv V^{+}(1,0)-V^{+}(0,1).$$

Subtracting Eq. (11) from Eq. (12) and simplifying, we get

$$\Delta=(1-\delta\,(1-\rho))^{-1}\left(\pi(1,0)-\pi(0,1)+\frac{1}{2}\,\rho^2\right)>0 \tag{15}$$

where the inequality follows from part (b) of Assumption 3. Together with Eq. (13), this implies that

$$V(1,0)>V(1)>V(0,1). \tag{16}$$

Substituting Eq. (14) into Eq. (13), imposing $\pi(0,1)=\pi(1,0)$, and simplifying we get

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

where $k\equiv\frac{\delta}{1-\delta}\,\pi(1)$ 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 $\rho(0,1)\to 0$ as $\pi(0,1)-\pi(1,0)\to 0$. Given that $\rho(0,1)\to 0$, it follows from Eq. (15) that $\Delta\to 0$, and from Eq. (14) that $V(0,1)-V(1)\uparrow 0$ and $V(1,0)-V(1)\downarrow 0$.

Intuitively, if $\pi(0,1)\approx\pi(1,0)$, then firm 0 knows that, as long as we remain in the current state, both firms make approximately the same profit. This means that 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 $V(1)$. 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 5.** We now show that, under no standardization at (0, 0), the equilibrium level of R&D is greater and so is firm value. This implies that the equilibrium consists of firms opting for maintaining two standards when at state (0, 0).

The argument is illustrated in Fig. 6, where we plot ρ on the horizontal axis and V on the vertical axis. V stands for $V(0,0)$ and ρ for $\rho(0)$ or $\rho(0,0)$, depending on the equilibrium under consideration. Consider first the equilibrium with standardization at state (0, 0).

Two mappings are depicted in Fig. 6. The mapping $\Phi_1(V,\rho)$ is given by Eq. (5), that is,

$$V=\frac{\pi(0)+\delta\left(1-(1-\rho)^2\right)V(1)-\frac{1}{2}\rho^2}{1-\delta\,(1-\rho)^2}$$

where $V=V(0,0)$ and $\rho=\rho(0)$. This gives the value in state (0, 0), under the standardization candidate equilibrium, assuming that firms choose an R&D success probability $\rho=\rho(0,0)$. Notice that V is a concave, non-monotonic function of ρ. Essentially, this results from our assumption that the cost of R&D is a convex function of ρ. The fact that this is a non-monotonic function makes the analysis non-trivial: it does not suffice to state that non-standardization increases the level of ρ; we also need to show that this increases firm value.

The mapping $\Phi_2(V,\rho)$ is given by Eq. (7), that is

$$\rho=\frac{\delta(V(1)-V)}{1+\delta(V(1)-V)}.$$

This mapping gives equilibrium $\rho=\rho(0,0)$ as a function of value $V=V(0)=V(0,0)$, again under the candidate equilibrium whereby there is standardization at every state.

Finally, the equilibrium levels $\rho(0,0)$ and $V(0)=V(0,0)$ are given by the intersection of the two mappings, that is, by point S, where S stands for single standard.

Consider now an alternative equilibrium whereby firms fail to agree on a common standard at state (0, 0). Suppose that $\pi(0,0)=\pi(0)$, that is, returns from standardization at state (0, 0) are nil. Then the value at state (0, 0), that is, $V(0,0)$, is still given by Eq. (5). In other words, if $\pi(0,0)=\pi(0)$ then Eq. (8) reduces to Eq. (5).

Regarding the mapping $\Phi_2(V,\rho)$, $\rho=\rho(0,0)$ is now given by Eq. (10), that is

$$\rho=\frac{\delta(V(1,0)-V)}{1+\delta(V(1,0)-V)}.$$

Since $V(1,0)>V(1)$, this corresponds to a shift of $\Phi_2(V,\rho)$ to the right. (This is a general feature that can be checked readily by differentiating the above equation.) Since $V(1,0)-V(1)\downarrow 0$, as shown in the previous step, it follows that the new equilibrium is given by a point like point D, where both V and ρ are greater than in the previous candidate equilibrium.

Notice that, in making the above argument, we assumed $\pi(0,0)=\pi(0)$ and $V(1,0)-V(1)\downarrow 0$, which in turn results from $\pi(1,0)-\pi(0,1)\to 0$. More generally, given the continuity of all the relevant

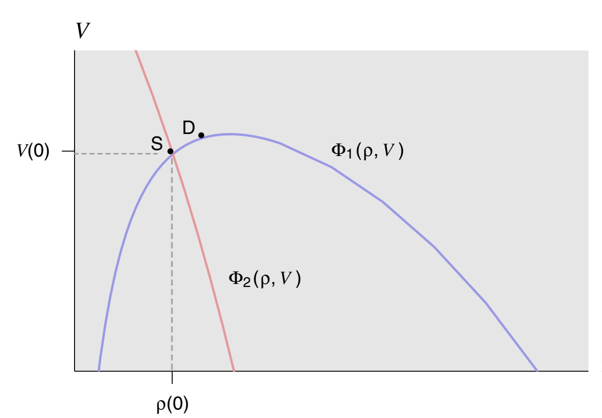

Fig. 6. Proof of Proposition 1.

functions, the argument extends for $\pi(1,0) - \pi(0,1) < \epsilon$ and $\pi(0,0) - \pi(0) < \epsilon^2$, as in the Proposition's text.

All we are left to show is that the slope of $\Phi_1(\rho,V)$ at point S is positive, as indicated in Fig. 6. Consider the equilibrium with standardization at (0, 0). Suppose that, during the second part of the period (where the state is now (0)), both firms were to increase ρ by the same amount starting from the equilibrium level $\rho(0)$. Setting $\widetilde{\rho} = \rho$ in Eq. (6) and differentiating with respect to ρ, we get

$$\frac{dV(0)}{\rho} = \frac{\delta\, 2\, (1-\rho)(V(1)-V(0))}{1-\delta(1-\rho)^2} - \rho.$$

Substituting Eq. (7) for ρ, and simplifying, we get

$$\frac{\frac{dV(0)}{\rho} = \delta(V(1)-V(0))}{1+\delta(V(1)-V(0))\left(\frac{2}{1-\delta\ (1-\rho)^2-1}\right) > 0}.$$

We finally conclude that it cannot be an equilibrium for firms to agree on a common standard at state (0, 0) ■.

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.

References

Arthur, W. Brian, 1989. Competing technologies, increasing returns, and lock-in by historical events. The Economic Journal 99, 116–131.

Brandenburger, Adam, Stuart, Harborne, 2007. Biform games. Management Science 53 (4), 537–549.

Cabral, Luís, 2011. Dynamic price competition with network effects. Review of Economic Studies 78, 83–111.

Cabral, Luís, Kretschmer, Tobias, 2006. Standards battles and public policy. In: Greenstein, S., Stango, V. (Eds.), Standards and Public Policy. Cambridge University Press, Cambridge.

Chiao, B., Lerner, J., Tirole, J., 2007. The rules of standard setting organizations: an empirical analysis. Rand Journal of Economics 38, 905–930.

Choi, Jai-Pil, 1996. Standardization and experimentation: ex ante vs. ex post standardization. European Journal of Political Economy 12, 273–290.

Church, Jeffery, Gandal, Neil, 1993. Complementary network externalities and technological adoption. International Journal of Industrial Organization 11 (2), 239–260.

Corts, Kennet, Lederman, Mara, 2009. Software exclusivity and the scope of indirect network effects in the US video game market. International Journal of Industrial Organization 27, 121–136.

David, Paul, Greenstein, Shane, 1990. The economics of compatibility standards: an introduction to recent research. Economics of Innovation and New Technology 1 (1–2), 3–41.

Ellison, Glenn, Fudenberg, Drew, 2003. Knife-edge or plateau: when do market models tip? Quarterly Journal of Economics 118, 1249–1278.

Erkal, Nisvan, Minehart, Deborah, 2007. Optimal sharing strategies in dynamic games of research and development. Department of Justice Working Paper EAG 07–7, April 2007.

Farrell, Joseph, Saloner, Garth, 1985. Standardization, compatibility, and innovation. Rand Journal of Economics 16, 70–83.

Farrell, Joseph, Saloner, Garth, 1988. Coordination through committees and markets. Rand Journal of Economics 19, 235–252.

Farrell, Joseph, Simcoe, Timothy, 2012. Choosing the rules for consensus standardization. Rand Journal of Economics 43 (2), 235–252.

Gandal, Neil, Salant, David, Waverman, Leonard, 2003. Standards in wireless telephone networks. Telecommunications Policy 27, 325–332.

Greenstein, Shane, Rysman, Marc, 2007. Coordination costs and standard setting: lessons from 56k modems. In: Greenstein, S., Stango, V. (Eds.), Standards and Public Policy. Cambridge University Press, Cambridge, pp. 123–159.

Katz, Michael L., Shapiro, Carl, 1985. Network externalities, competition and compatibility. American Economic Review 75, 424–440.

Kretschmer, Tobias, 2008. Splintering and inertia in network industries. Journal of Industrial Economics 56 (4), 685–706.

Leiponen, A., 2008. Competing through cooperation: standard setting in wireless telecommunications. Management Science 54, 1904–1919.

Mitchell, Matthew, Skrzypacz, Andrzej, 2006. Network externalities and long-run market share. Economic Theory 29, 621–648.

Rubinstein, Ariel, 1982. Perfect equilibrium in a bargaining model. Econometrica 50 (1), 97–109.

Salant, David, Waverman, Leonard, 1998. The Use of Standard Setting as a Means of Facilitating Cartels and Its Trade Effects. International Competition Policy Advisory Committee, US Department of Justice (November).

Salant, David, Waverman, Leonard, 1999. Testimony at International Competition Policy Advisory Committee, US Department of Justice (May).

Simcoe, Timothy, 2012. Standard setting committees: consensus governance for shared technology platforms. American Economic Review 102, 305–336.