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ONE-WAY COMPATIBILITY, TWO-WAY COMPATIBILITY AND ENTRYIN NETWORK INDUSTRIES

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Abstract

We study the strategic choice of compatibility between two initially incompatible network goods in a two-stage game played by an incumbent and an entrant firm. Compatibility may be achieved by means of a converter. We derive a number of results under different assumptions about the nature of the converter (one-way *vs* two-way), the existence of property rights and the possibility of side payments. With incompatibility, entry deterrence occurs for sufficiently strong network effects. In the case of a two-way converter, which can only be supplied by the incumbent, incompatibility will result in equilibrium unless side payments are allowed and the network externalities are sufficiently low. When both firms can build a one-way converter and there are no property rights on the necessary technical specifications, the unique equilibrium involves full compatibility. Finally, when each firm has property rights on its technical specifications, full incompatibility is observed at the equilibrium with no side payments; when these are allowed the entrant sells access to its network to the incumbent which refuses to do the same and asymmetric one-way compatibility results in equilibrium. The welfare analysis shows that the equilibrium compatibility regime is socially inefficient for most levels of the network effects.

J.E.L. codes: L13, L15, D43.

Keywords: Network externalities, one-way compatibility, two-way compatibility, entry.

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1 Introduction

The two related issues of compatibility and network externalities have attracted much attention in the economic literature. The existence of significant demand externalities is recognised in a number of markets. The essential feature of demand externalities is that the individual benefit from, and consequently the individual willingness to pay for, consumption of the good (service) increases with the number of people consuming the same good (service) or a compatible one. There are many sources of externalities, ranging from the presence of a physical network connecting consumers, as with telecommunications, to the case of a virtual network, as with computer softwares and other goods for which a *community of interest* effect arises.

In a significant number of such network industries (software, media, videogames, hardware, payment systems), largely dominant firms own proprietary technologies and/or standards that are not licensed to competitors. These niche competitors use their own technology which is incompatible with that of the dominant firm. Incompatibility, which affects the size of each firm's relevant network, is often not due to technical reasons, but is rather a consequence of the strategic choices made by firms.

Network effects engender different incentives for compatibility between established firms and entrants. For an established firm, the network formed by its installed base of consumers plays a strategic role since it confers an advantage on late comer rivals. It is therefore a valuable asset to defend, and one way to achieve this is by maintaining incompatibility with the entrant. On the other hand, for late comers compatibility with the incumbent's network may be the only way to gain a significant market share. Examples of this kind of situation abound. In the videogame industry, Nintendo was dominant in the 32-bit system and denied Atari permission to include an adapter to play Nintendo cartridges on Atari's machines. In the spreadsheet market, Borland designed its Quattro Pro spreadsheet so that it could import Lotus files and also copied the menu structure used by Lotus, the then dominant player with its Lotus 1-2-3. In reaction Lotus sued Borland for copyright infringement. One common tactic used by entrant firms faced with an incompatible incumbent is to add an adapter/converter or somehow to interconnect with the established technology (see Shapiro and Varian, 1998).

We analyse the conflicting incentives to which incumbent and entrant firms are subject when deciding whether or not to make their good compatible with the one produced by the rival by means of a converter. We do so under a variety of assumptions about the nature of the converter and the existence of property rights.

In our model an incumbent firm produces a durable good subject to network externalities. In period 1 the firm is the only producer and it faces entry in the second period by a potential entrant which supplies an homogeneous good incorporating a different technology. The assumption of homogeneity of the goods allows us to concentrate on the effects of compatibility choices and of installed bases of users on the pattern of entry and on the feasibility of entry deterrence. Conceptually, the installed base of a network good serves the same purpose of irreversible investment in physical capacity for the incumbent. Whilst in the absence of switching costs, output decisions have no commitment value, in the presence of network externalities and incompatibility, the incumbent can strategically choose the level of first period output in order to reduce the rival's scale of entry or to preempt it altogether.

We explore different scenarios of the way in which compatibility is achieved. In particular we consider the following three cases:

1. Compatibility through two-way converters supplied either by the incumbent or the entrant;

2. Compatibility through one-way converters supplied by the incumbent and the entrant;

3. Compatibility through one-way converters supplied by the incumbent and the entrant, subject to disclosure of each other's technical specifications.

In the first case, one of the two firms may produce, at no cost, a two-way converter which induces perfect compatibility between the two networks of users. If the converter is supplied by the incumbent then this scenario is equivalent to the case, widely studied in the literature, of licensing where the incumbents invites the entry of a compatible rival. In the second case, each firm can freely design a converter which allows its customers to communicate with the customers of the rival firm. Finally, in the third scenario, firms have the possibility to deny to the rival the technical specifications needed to build any converter.

Examples of each of the three scenarios can be easily found. A two-way converter corresponds to the capability, provided by many softwares, of reading and saving in the rival's format. In text processing, for example, Word allows the user to read and save in WordPerfect's format. The unilateral provision of this feature allows users of both softwares to communicate, so that the relevant installed base for each software becomes the entire population of adopters of text processing softwares. In the streaming media industry both Apple's QuickTime and Microsoft Windows Media Player can playback and save in each other's proprietary format (.mov and .wav respectively), and in the other common format MPEG (Moving Picture Experts Group).

Examples of one-way converters can take different forms. Software may allow reading but not saving in a different format or viceversa. It is interesting to note the difference between these two cases. If software A allows the reading but not the saving of files produced with software B, then users of the former can read files from the latter but cannot exchange their files with the users of software B. In the opposite case things are reversed. As mentioned above, Borland Quattro Pro allowed the user to import files generated with Lotus 1-2-3 but not to save files in Lotus format. Since the late 80's, when Apple Computers installed the so called "Hyperdrive" diskette drive, which was able to read DOS-formatted diskettes used on Intel-based PCs, Mac users have been able to read files produced on Intel-based computers, but files on Mac-formatted supports are not readable on Wintel machines.

Examples of one-way converters include the so-called *viewers* introduced by a number of commercial software vendors. These are downgraded free versions of the main software that allow non-users to view and print files prepared with their software. These viewers yield the same result as produced by a converter which allows saving but not reading in a different format, the only difference being that the *transaction cost of conversion* accrues to the users of the other software.[1]

The story of Nintendo *vs* Atari as mentioned above best illustrates the third scenario. Atari tried to achieve one-way compatibility, but it lacked the intellectual property rights to include an adapter in its machines to play Nintendo cartridges.

As said above, we analyse the issue of compatibility under network externalities in an industry where an incumbent firm faces a potential entrant. We contemplate various forms of compatibility between the incumbent and the entrant's technology and, when appropriate, we also allow for side payments between firms. This is of particular relevance in high-tech industries where firms very often own intellectual property rights on their standards and release the technical specifications needed to build a converter only after the payment of a licence. We show how the incumbent firm can use its installed base strategically in order to keep the rival out of the market.

[1] Examples of such viewers are Word Viewer, PDF Viewer, Excel Viewer.

We derive the following results. In the first scenario where compatibility can only be two-way, the incentives for the entrant are obvious since it always wants to build a converter. By contrast, if the adapter can only be supplied by the incumbent (e.g. because it has property rights on its standard, or it is able to forbid the entrant to build and adopt an adapter), in the absence of side payments, incompatibility is always observed in equilibrium, and this enables the incumbent, when network externalities are sufficiently large, to deter entry. Allowing for side payments, we derive a threshold level of network externalities such that for lower levels of the externality total industry profits are larger under compatibility than incompatibility: a sufficient condition for two-way compatibility in equilibrium.

In the second scenario, where the incumbent and the entrant can freely decide to build a one-way converter, full compatibility proves the be the equilibrium. Finally, and more interestingly, in the third scenario where each firm has property rights on its technology and can block the rival from building a one-way adapter, we show that the nature of the equilibrium is dependent on the strength of the network externalities and the possibility of side payments. If network externalities are sufficiently high for the incumbent to be able to deter entry, then, independently of the presence of side payments, the incumbent refuses to disclose its private information and entry deterrence occurs. For lower levels of the externality whilst in the absence of side payments the unique equilibrium of the game is full incompatibility, with side payments we obtain an asymmetric equilibrium compatibility regime, in which the entrant sets a positive access fee and sells access to its post-entry installed base to the incumbent. The latter pays the fee and builds a one-way converter but, at the same time, it does not licence the rival, which it is therefore forced to enter with an incompatible technology. This equilibrium is new in the literature and illustrates a novel strategy for an incompatible entrant: allowing the incumbent access to its (smaller) network for a fee and sharing part of the increase in the potential surplus for the incumbent. These results have interesting welfare implications that we explore in the last part of the paper. We show that, depending on the compatibility regime taken into account, market forces may lead to inefficiency. Since Katz and Shapiro (1985) and Katz and Shapiro (1986), the presence of market failures in industries with network externalities is a well known result. The novelty of the paper is that inefficiency also depends on the type of compatibility (one-way vs two-way).

1.1 Related literature

There is a well developed body of literature on entry, compatibility and standardisation in network industries,[2] and it focuses mainly on the analysis of two-way compatibility. This is usually introduced via the construction of a two-way adapter, or the disclosure of technical specification by the incumbent firms which invite the entry of new competitors through licencing.[3]

To the best of our knowledge, the only paper that discusses the issue of one-way interface standards in the context of competition between incompatible technologies is Foros (2007) which analyses how the price strategies employed by the firms affect their incentives to allow/deny the rival to be one-way compatible (in this latter case, with the so called "walled garden" strategy) and demonstrates that this latter strategy is more likely when firms adopt price discrimination as opposed to linear pricing. This result contrasts with the conclusion we derive under the third scenario where the firm can unilaterally prevent the rival from providing a one-way converter. Whereas in Foros (2007) both firms may have an incentive to unilaterally provide one-way compatibility, provided that both use linear pricing, in our model, in the absence of side payments, incompatibility results in equilibrium. This different result is driven by the differing assumptions on the timing of the game (symmetric and one-period in Foros, asymmetric and two-period in our model) and the type of competition between firms (price or quantity respectively).

Relevant to our first scenario is the seminal paper by Katz and Shapiro (1985), where firms may achieve full (two-way) compatibility through an adapter which can either be built unilaterally by a single firm or be the outcome of a multilateral agreement to define a common standard. Incentives to build the adapter are found to depend strongly on the sizes of the firms' networks. The setting of Katz and Shapiro's paper is different from ours in that it lacks a dynamic structure, differences in network sizes are exogenously given, and the analysis in mostly focused on comparison between private *vs* social incentives towards compatibility. Finally, the role of one-way converters is not analysed. Our results for the scenario of two-way compatibility further qualify the results of Katz and Shapiro (1985). With side payments we show that full compatibility is achieved as long as network externalities are not too strong; this is a possibility envisaged in the discussion of their Proposition 8; our model isolates the strength of the network externalities as the driver of the

[2] See Matutes and Regibeau (1996) and Economides (1996b) for excellent surveys.

[3] The strategic use of one-way compatibility by providers of network goods is briefly mentioned in Shy (2001).

resulting compatibility equilibrium regime.

Farrell and Saloner (1992) develop a model similar to that of Katz and Shapiro (1985). They discuss private and social incentives to build a two-way adapter which gives users of a given technology access to the rival's installed base of users and enables them to benefit from larger network externalities. These authors show that in order to preserve its network size, a dominant firm will intentionally raise the rival's cost of building the adapter.

Further discussion of the relation of our results with those of the above mentioned papers is conducted in subsequent sections, where the results are derived.

The paper is organised as follows: section 2 presents the basic framework, section 3 describes the game and the firms' payoffs; the strategic analysis of compatibility is given in section 4. The welfare analysis is carried out in section 5.

2 The model

The model has two periods. In the first a single firm serves the market and builds an installed base of customers; in the second period entry by a rival firm may occur and firms compete on quantities. We explore three different scenarios of the way in which compatibility is achieved:

1. Compatibility through two-way converters supplied either by the incumbent or the entrant;
2. Compatibility through one-way converters supplied by the incumbent and the entrant;
3. Compatibility through one-way converters supplied by the incumbent and the entrant, subject to disclosure of each other's technical specifications.

There are four possible outcomes: *i*) full compatibility between the entrant and the incumbent (two-way compatibility), *ii*) full (two-way) incompatibility, *iii*) the incumbent is one-way compatible with the entrant and *iv*) the entrant is one-way compatible with the incumbent.

With full compatibility, users of the two technologies communicate perfectly and the relevant network size is given by the total number of users; if incumbent and entrant are fully incompatible, then each technology has its own relevant network equal to the number of users adopting it. Finally, with one-way compatibility the users of the compatible technology can communicate with the users of the rival technology but not viceversa. Therefore, the relevant network for the compatible technology is the total number of users, while the relevant network for the incompatible technology is given by the number of users adopting it.

2.1 Consumers

Each consumer buys at most one unit of the good, which is durable. Consumers base their purchase decisions on expected network sizes. The population of consumers is uniformly distributed along the interval $[-\infty, A]$, with $A > 0$, according to the individual *basic* willingness to pay r.[4]

Following Katz and Shapiro (1985), the network externalities are captured by a function V of the expected size of the network that a consumer is deciding to join, so that, for given expectations the *total* willingness to pay for a consumer of type r' is given by a $r' + V$. We assume that the function V is monotonically increasing in the expected size of the network; specifically we assume that $V' > 0$ and $V'' \leq 0$.

We define $\hat{x}_I^1$ as the expected network size of the incumbent in period 1 (i.e. the total number of expected sales in the first period). In the second period, if entry occurs, consumers, prior to their purchasing decision, observe Firm 1's realised output in period 1 (i.e. Firm 1' installed base) and form expectations about the network size of the two firms. Expectations on firms' network size are related to the form of compatibility (two-way vs one-way compatibility) adopted by each firm. We denote with $\hat{y}_i$ the expected network size of firm i, $i = I, E$, in period 2 with:

$$\hat{y}_I = x_I^1 + \hat{x}_I^2 + \mu \hat{x}_E^2, \quad \text{and} \quad \hat{y}_E = \hat{x}_E^2 + \phi(\hat{x}_I^2 + x_I^1), \tag{1}$$

where $\hat{x}_i^2$ represents the expected number of consumers purchasing the good from firm i in period 2.[5]

When the incumbent and the rival technologies are fully compatible, $\mu = \phi = 1$; in this case, users' expectations about network sizes are equal to the sum of the two firms' expected sales. When technologies are fully incompatible, formally when $\mu = \phi = 0$, expectations are formed with respect to each firm's total expected sales.[6]

[4] The support of r has no finite lower limit in order to avoid corner solutions where all consumers enter the market. The assumption of a uniform distribution yields linear demand functions.

[5] Henceforth E and I are used to denote the entrant and the incumbent respectively.

[6] Compatibility levels, however, may take intermediate values between 0 and 1. We do not consider this possibility. This does not result in a severe loss because, given the assumption that the cost of compatibility, through converters, is zero, one can easily show that the entrant will always choose full compatibility, and that the incumbent will prefer extreme to intermediate values.

One-way compatibility is the intermediate case, formally when $\mu = 1$, $\phi = 0$ or $\mu = 0$, $\phi = 1$, in which only one firm is compatible with the other and not viceversa: for example if $\mu = 1$ and $\phi = 0$, the incumbent firm, by means of an adapter or hardware interface, is compatible with the rival technology while the opposite does not hold. In this case, since users of the incumbent product can freely communicate with the rival's users, they form their expectations on the total amount of output sold, while the same does not hold for those who adopt the entrant's technology. In other words, if the variety produced by the incumbent is compatible with that produced by the entrant, $\hat{y}_I$ contains the installed base of this latter.

2.2 Firms

In period 1 the incumbent is the only active firm; in period 2 entry by a second firm may occur and the two firms compete *à la Cournot*. The two firms incur constant marginal cost (which we normalize to zero) and there is no other fixed cost. The two goods produced are homogeneous, in the sense that for equal expected network sizes and prices, the consumers are indifferent between the two. We can conceive the two goods as performing the same tasks, or as being equivalent in all characteristics but incorporating different technologies (word processors, spreadsheets and many other software packages have this property). We do not explicitly model why technologies differ. Indeed, the focus of our analysis is not on the introduction of new technologies by new entrants; rather, by assuming exogenously given technological differences, we concentrate on the strategic use of converters/emulators/plug-ins to obtain compatibility.

When firms set their outputs, they take consumers' expectations as given. This assumption is common in the literature, and implies that firms cannot affect consumers' expectations because they cannot credibly commit to a certain level of output.[7]

2.3 Demand

2.3.1 Demand in period 1

In the first period, consumers are confronted with a binary decision: buy in t=1 or wait until t=2. They take their first period consumption decisions rationally so as to maximise total expected net surplus over both periods.

[7] See Katz and Shapiro (1985) and Economides (1996b) among others.

Let $CS_I^1 = r + V(\hat{x}_I^1)$ be the expected first period gross surplus of the type r consumer who buys from the incumbent, and let $CS_i^2 = r + V(\hat{y}_i)$ be the expected gross surplus from belonging to network $i = I, E$ in period 2. A consumer behaving rationally buys in period 1 if and only if the following two conditions are satisfied:

$$CS_I^1 - p_I^1 + CS_I^2 \geq 0, \tag{2}$$

$$\geq 0 + CS_i^2 - p_i^2, \qquad i = I, E \tag{3}$$

where p_i^t is the price charged by firm i at time t. The first condition ensures that, by buying in period 1, the consumer enjoys positive total net surplus over the two periods; condition (3) ensures that buying in $t = 1$ is better than buying in $t = 2$.

If entry occurs, at the equilibrium at time t=2, the consumer must be indifferent between buying from the incumbent or the entrant; formally:

$$p_I^2 - V(\hat{y}_I) = p_E^2 - V(\hat{y}_E). \tag{4}$$

Therefore expressions (2) and (3) become, respectively,[8] $r \geq \frac{1}{2}\left[p_I^1 - V(\hat{x}_I^1) - V(\hat{y}_I)\right] \equiv \varphi$, and $r \geq -V(\hat{x}_I^1) + p_I^1 - p_I^2 \equiv \psi$. It turns out that, in equilibrium, we need to consider the second constraint only; indeed, which of the two constraints is binding in equilibrium depends on the sign of $p_I^2 - p_I^1/2 - \left[V(\hat{y}_I) - V(\hat{x}_I^1)\right]/2$. If this is negative(positive) then the second(first) constraint is binding. Suppose for the moment that $p_I^2 > p_I^1/2 + \left[V(\hat{y}_I) - V(\hat{x}_I^1)\right]/2$; it is easy to show that second period demand for the incumbent is zero. This result is accomplished by the incumbent fixing the price p_I^2 sufficiently high. This pricing plan, as is well known from the literature around Coase's Conjecture, is time inconsistent in that chocking second period market is ex-post suboptimal for the monopolist. Since the firm has no way of committing itself to such course of action, consumers will not believe that the second period price will be set at a sufficiently high level. As a consequence, we can concentrate on the second condition.

The total number of consumers meeting this condition is $x_I^1 = A - \psi$; therefore the market clearing condition implies that the first period demand function with optimising agents is simply:[9]

$$p_I^1 = A + V(\hat{x}_I^1) + p_I^2 - x_I^1. \tag{5}$$

[8]Expressions (2), (3) and (4) imply that consumers who bought in period 1 do not switch to the entrant's good in period 2.

[9]To be noted is that only the expectations about the first period network size enter into the first period demand

2.3.2 Demand in period 2

Second period demand is derived as a residual of first period demand given the realised first period output. From the necessary condition for two active firms in the second period given by (4), let $\eta = p_i^2 - V(\hat{y}_i)$ be the common level of the *hedonic* prices. According to the assumption of uniformly distributed population, and recalling that x_I^1 consumers have already purchased the good in the first period, the number of consumers for which $r > \eta$ is equal to $A - x_I^1 - \eta$. Duopoly equilibrium implies the following market clearing condition:

$$A - x_I^1 - \eta = x_I^2 + x_E^2 \equiv x_{tot},$$

which can be rewritten as

$$A - x_I^1 + V(\hat{y_I}) - p_I^2 = A - x_I^1 + V(\hat{y_E}) - p_E^2 = x_{tot},$$

where x_{tot} is the total output in the second period. It follows that the second period demand functions are:

$$p_I^2 = A - x_I^1 + V(\hat{y_I}) - x_{tot} \quad \text{and} \quad p_E^2 = A - x_I^1 + V(\hat{y_E}) - x_{tot}. \tag{6}$$

In the following section we derive, by backward induction, the Cournot equilibrium in the second period and the incumbent's optimal output level in the first, contingent on the compatibility choices made by the firms. Given the assumption of exogenous expectations, there is a continuum of equilibria in both periods. We restrict our attention to the *fulfilled expectations* equilibria, namely those where the expected network sizes correspond to the actual ones.

externality function. Although counterintuitive, this has a clear explanation and it does not mean that consumers do not account for $\hat{y}_i$ when purchasing the good in the first period. Consider (2): the expected net surplus from buying in t=1 naturally includes two gross surpluses: CS_I^1 and CS_I^2. Expectations on second period network size are in CS_I^2; when considering the balance between buying today or waiting until the next period, which determines the demand in the first period, see (3), CS_I^2 cancels out with the analogous surplus obtained if the good is demanded in the second period. In other words, the additional benefit of the second period network externality on first period consumers' valuations is enjoyed also when buying in the second period, and it is therefore irrelevant when the first period decision has to be taken.

3 The fulfilled expectations equilibrium

The equilibrium concept we use is that of the *fulfilled expectations* equilibrium (FEE) first introduced in the literature on networks by Katz and Shapiro (1985) and widely adopted by other authors. In each period we restrict our attention to those equilibria which satisfy the condition that expected network sizes equal the actual ones. Ex-post consumers' expectations are correct.

The assumption of FEE is also useful in this two stage game; consumers form expectations about second period networks at the beginning of both periods: therefore we should have both first period and second period expectations about x_i^2.[10]

The existence and uniqueness of the equilibrium cannot be generally taken for granted and depend on the exact specification of the externality function $V(\cdot)$. In order to solve the model and to characterise the solutions, we need to specify the functional form of the externality function. We assume the following:

Assumption 1. *The externality function is linear:* $V(\hat{x_I}) = \theta \hat{x}_I$ *and* $V(\hat{y}_i^2) = \theta \hat{y}_i^2$, *with* $\theta \in [0, \bar{\theta}]$.

The parameter θ measures the strength of network externalities: for given expectations about network size, a higher θ implies a greater willingness to pay to belong to that network. The strength of network externalities may depend on a number of factors and basically reflects the importance and/or the benefits consumers attach/derive from belonging to the same community of users. These effects are generally stronger in physical networks, such as the telephone or the internet, and may be very marked in virtual networks such as credit cards, ATM machines, software and video games consoles.[11] θ is bounded above; we will show that this is required to ensure the existence, uniqueness and stability of the FEE.[12] The admissible upper bound $\bar{\theta}$ varies according

[10] By restricting the equilibria to those that match expectations, first and second period expectations must be identical at the equilibrium. For the sake of simplicity, we can therefore make no distinction between expectations formed at the beginning of the first and second stage. This clearly does not affect the solution of the game but makes the notation far less cumbersome.

[11] Empirical evidence of network effects has been found in a number of product categories ranging from spreadsheets, (Brynjolfsson and Kemerer, 1996), to databases (Gandal, 1995), networking equipment (Forman and Chen, 2003), peer-to-peer networks (Asvanund *et al.*, 2004) and DVD players (Dranove and Gandal, 2003). For a discussion on the importance of network externalities in shaping the business environment of firms see Andal-Ancion (2003).

[12] Note that with a strictly concave externality function, the existence of FEE is more easily guaranteed, although additional assumptions are needed to ensure uniqueness.

to the kind of compatibility considered and it ranges between 0.704 and 1.

3.1 FEE Payoffs

We are now ready to derive the FEE payoffs for the four possible compatibility regimes of the game: full compatibility ($\mu = 1$, $\phi = 1$), full incompatibility ($\mu = 0$, $\phi = 0$) and partial compatibility (either $\mu = 1$, $\phi = 0$ or $\mu = 0$, $\phi = 1$).

3.1.1 Second period Cournot equilibrium

Conditional on entry and given consumers' expectations, in the second period firms compete on output. Firms face the demand function (6); given the first period incumbent's installed base x_I^1, firm j's maximisation problem is therefore:

$$\max_{x_j^2} \quad \pi_j^2 = (A - x_I^1 + \theta\, \hat{y}_j - x_{tot})\, x_j^2. \tag{7}$$

This is a standard Cournot oligopoly; simple calculations show that the incumbent and entrant equilibrium outputs are respectively:

$$x_I^2 = \frac{A - x_I^1 + 2\theta\, \hat{y}_I - \theta\, \hat{y}_E}{3}, \quad \text{and} \quad x_E^2 = \frac{A - x_I^1 + 2\theta\, \hat{y}_E - \theta\, \hat{y}_I}{3}. \tag{8}$$

These expressions give the quantity produced by each firm in the second period as a function of consumers' expectations about each firm network size and given that x_I^1 customers have already purchased the good in the first period. FEE is derived by setting expected sales equal to the actual ones; formally: $\hat{y}_I = x_I^1 + x_I^2 + \mu x_E^2$ and $\hat{y}_E = x_E^2 + \phi(x_I^2 + x_I^1)$. Solving the system of equations (8) with fulfilled expectations, firms' outputs in the second period given the first period installed base are:

$$x_I^2(x_I^1) = \frac{A(\theta(1-\mu) - 1) + (\theta(\theta(\mu\phi - 1) - \phi - \mu + 3) - 1)x_I^1}{3 + \theta(\theta(1 - \mu\phi) + \mu + \phi - 4)}, \tag{9}$$

$$x_E^2(x_I^1) = \frac{A(\theta(\phi - 1) + 1) + (\phi\theta - 1)x_I^1}{3 + \theta(\theta(1 - \mu\phi) + \mu + \phi - 4)}. \tag{10}$$

Expressions (9) and (10) give, for the different values of the compatibility parameters μ and ϕ, the output produced by the incumbent and by the entrant under the different compatibility regimes. Existence and uniqueness of the fulfilled expectations second period Cournot equilibrium are proved in the Appendix.

3.1.2 First period equilibrium

In the first period, the incumbent acts as a monopolist and recognises that its first period output decision has an impact on second period profits. The incumbent's maximisation problem in the first period is the following:

$$\max_{x_I^1} \quad \pi_I = p_I^1\, x_I^1 + p_I^2\, x_I^2(x_I^1), \tag{11}$$

where p_I^1 is the first period demand faced by the incumbent as in (5), while p_I^2 is the incumbent's equilibrium price in the second period given in (6) and $x_I^2(x_I^1)$ is given in (9). Solving the incumbent's maximisation problem, we derive the first period production given consumers' expectations on first period incumbent installed base $\hat{x}_I^1$:[13]

$$x_I^1(\hat{x}_I^1) = \frac{(10+(4\mu+\phi-9)\theta+(2\phi+4\mu-1-5\mu\phi)\theta^2)A-((3\mu\phi-3)\theta^3+(12-3\phi-3\mu)\theta^2-9\theta)\hat{x}_I^1}{(\phi^2\mu-\phi+2-2\mu\phi)\theta^3+(2\mu-9\mu\phi-\phi^2+4+4\phi)\theta^2+(9\phi-33+8\mu)\theta+22}. \tag{12}$$

The fulfilled expectations equilibrium output in the first period is given by:

$$x_I^1 = \frac{(10+(4\mu+\phi-9)\theta+(2\phi+4\mu-1-5\mu\phi)\theta^2)A}{(\mu\phi-\phi-1+\phi^2\mu)\theta^3+(16-\phi^2+\phi-9\mu\phi-\mu)\theta^2+(9\phi-42+8\mu)\theta+22}. \tag{13}$$

Uniqueness and stability of the FEE in period 1 are proved in Appendix. The FEE payoffs for the incumbent and the entrant in the four possible outcomes of the game are:[14]

$$\pi_{c,c}^I = \frac{A^2(176-8\theta^3-192\theta+69\theta^2)}{(6\theta^2-25\theta+22)^2}, \qquad \pi_{c,c}^E = \frac{(\theta-4)^2A^2}{(6\theta^2-25\theta+22)^2},$$

$$\pi_{c,i}^I = \frac{A^2(176-60\theta^3-252\theta+11\theta^4+155\theta^2+6\theta^5)}{(22-\theta^3+15\theta^2-34\theta)^2}, \qquad \pi_{c,i}^E = \frac{(13\theta-\theta^2-4)^2A^2}{(22-\theta^3+15\theta^2-34\theta)^2},$$

$$\pi_{i,c}^I = \frac{A^2(176-104\theta^3+17\theta^4-\theta^5-368\theta+289\theta^2)}{(22+16\theta^2-2\theta^3-33\theta)^2}, \qquad \pi_{i,c}^E = \frac{(\theta-4)^2A^2}{(22+16\theta^2-2\theta^3-33\theta)^2},$$

$$\pi_{i,i}^I = \frac{A^2(176-96\theta^3-428\theta+2\theta^5+12\theta^4+343\theta^2)}{(22-\theta^3+16\theta^2-42\theta)^2}, \qquad \pi_{i,i}^E = \frac{(13\theta-\theta^2-4)^2A^2}{(22-\theta^3+16\theta^2-42\theta)^2},$$

where $\pi_{c,c}^I$ and $\pi_{c,c}^E$ are respectively the incumbent's and the entrant's total profits when both goods are compatible ($\mu = 1$, $\phi = 1$); $\pi_{c,i}^I$ and $\pi_{c,i}^E$ are total profits when the incumbent is one-way compatible with the entrant but not vice versa ($\mu = 1$, $\phi = 0$). Similarly, $\pi_{i,c}^I$ and $\pi_{i,c}^E$ are the profits when the entrant's product is compatible but not the incumbent's ($\mu = 0$, $\phi = 1$), and finally $\pi_{i,i}^I$ and $\pi_{i,i}^E$ are the payoffs with full incompatibility ($\mu = 0$, $\phi = 0$).

[13] It is easy to check that the second order condition is satisfied.

[14] These payoffs can be derived by plugging the FEE outputs for x_I^1, x_I^2 and x_E^2 into firms profit functions. The algebra, available on request, is particularly tedious and for the sake of brevity is omitted.

3.1.3 The strategic role of the installed base and entry deterrence

So far we have assumed that entry occurs in the second period. In some circumstances, this may not be the case and entry is deterred by the incumbent. The incumbent can use its first period output strategically in order to reduce the scale of entry by the rival in the second period. The output decision in the first period affects second period output for both firms.

Consider expressions (9) and (10); these give the incumbent's and the entrant's FEE outputs as a function of the incumbent's first period production and of the compatibility parameters μ and ϕ. Both these expressions are decreasing in x_I^1, but the impact on the rival's output is stronger. Consequently there exists a level of first period output, denoted with x_I^d, which is sufficient to ensure entry deterrence and a positive second period output for the incumbent. Equating (10) to zero yields:

$$x_I^d = \frac{A(\theta(\phi-1)+1)}{(1-\phi\theta)}, \qquad \phi \in \{0,1\}. \tag{14}$$

Whenever $x_I^1 \geq x_I^d$, entry is deterred. However, although entry deterrence is feasible, it is not necessarily optimal for the incumbent. In the next proposition we establish necessary and sufficient conditions for entry deterrence. The proofs of all the mathematical results are in the Appendix.

Proposition 1. *Entry deterrence occurs if and only if: i) the entrant is incompatible,* $\phi = 0$, *and ii)* $\theta \geq \theta^d = 0.315$. *Furthermore, if* $\theta \geq 0.394$ *entry is blockaded: pure monopoly output is sufficient to deter entry.*

The idea that the installed base of a network good can play a preemptive role that possibly deters entry has been studied by Fudenberg and Tirole (2000) in a different setting. The basic intuition is simple and it closely resembles that of the traditional case of irreversible investment. Both irreversible investment and installed base irrevocably alter the conditions under which second period competition occurs. For later use, we define the incumbent's FEE profits in the case where entry is deterred/blockaded, as follows:[15]

$$\pi^d = \begin{cases} A^2\theta(\theta^2 - 3\theta + 3) & \text{if} \quad \theta \in [0.315, 0.394] \\ 5\,\dfrac{(\theta-3)^2 A^2}{(\theta^2 - 9\,\theta + 10)^2} & \text{if} \quad \theta \in (0.394, \bar{\theta}] \end{cases}$$

[15] To compute this profit function, we use the outputs produced by the incumbent in the two periods; when entry is deterred, these output levels are $x_I^d = A(1-\theta)$ and $x_I^2 = A\theta$. If entry is blockaded, outputs are x_{mon}^1 and x_{mon}^2.

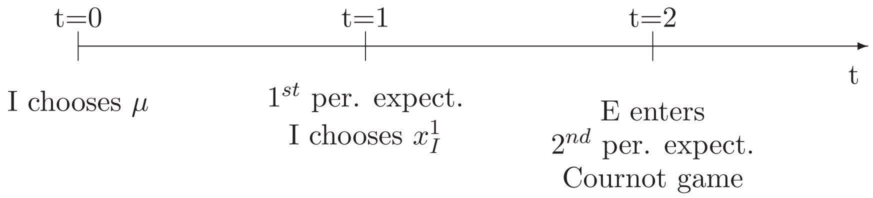

Figure 1: The time line with two-way converter

4 The strategic analysis of compatibility

We can finally solve for the market equilibrium in the three possible compatibility scenarios discussed above. For each case, we will present the market outcome both with and without technology licensing through side payments between the two firms.

4.1 Compatibility through two-way converter

In the first scenario, which is the one more often considered in the literature, compatibility is achieved through a two-way converter supplied either by the incumbent or the entrant. In this case the bridge between the two, otherwise incompatible, technologies is provided by means of a costless two-way converter[16] which allows users of both goods to *communicate* perfectly. This amounts to assuming that the use of the converter does not downgrade the performance.

The case where the decision to build the converter is up to the entrant is trivial: the entrant always chooses two-way compatibility. This scenario is equivalent to the asymmetric case of the construction of an adapter in Katz and Shapiro (1985) assuming zero cost of compatibility.

Consider now the case where the decision to build a converter is up to the incumbent in stage 1 and assume that the firm can credibly commit to such course of action either by making the converter available right at the beginning of t=1 or by including such a clause in the contract signed with its customers. Compatibility implies that at t=2 the two goods have the same network of customers which is equal to the total amount of output sold. When consumers in period 1 contemplate the purchase of the good, they incorporate this information into their expectations. The time line is represented in Figure 1.

[16]The assumption of zero costs for the converter is broadly consistent with the observation that converters are often a simple *add-on* to much more complex software whose development costs are much higher.

It should be noted that this case, which is trivial in Katz and Shapiro's (1985) set up, is interesting in the present two period model since the incumbent can profit from commitment to future (period 2) compatibility also in period 1 when it is the only producer. Compatibility accrues to the value of the incumbent's network in both periods through consumers' expectations. At the same time, it increases the rival's competitiveness because, with compatibility, the incumbent shares the first period installed base with the entrant, thus making its product perfectly homogeneous, in terms of network size, with the rival's. Furthermore, compatibility makes entry deterrence unfeasible owing to the sharing of the installed base. This scenario is not envisaged in Katz and Shapiro (1985) and in the subsequent literature, where the asymmetry between the installed base of the firms is assumed to be exogenously given and independent of the choice of compatibility regime.[17] Direct comparison of the equilibrium profits yields the following proposition.

Proposition 2. *If the construction of a two-way adapter is up to the incumbent, it always chooses incompatibility,* $\mu = 0$*; for* $\theta \geq \theta^d$ *entry is deterred.*

This proposition demonstrates that the negative effects of full compatibility on second period market share are never offset by the positive effect on period 1 profits and increased network size; therefore the incumbent never opts for the construction of the adapter.

Communications industries such as telecoms or the internet are those that best fit this scenario; in these industries, each network can deny access to its installed base of users and, eventually, compatibility is mandated to be reciprocal, i.e. two-way. What we observe, though, is an almost universal interoperability of networks achieved by means of interconnection/roaming agreements. This prompts us to consider another way of achieving full compatibility: networks agreements signed via side payments to obtain access to rivals' technology.

We investigate on this in the next Proposition:

Proposition 3. *If side payments are allowed, compatibility through a two-way converter is achieved in equilibrium provided that network effects are not too strong* ($\theta < 0.2$)*.*

To verify this result it is sufficient to check that when $\theta < 0.2$, total industry profits are larger with full compatibility than otherwise: $\pi^I_{c,c} + \pi^E_{c,c} > \pi^I_{i,i} + \pi^E_{i,i}$. If network effects are sufficiently weak, there exists a fixed fee that the entrant/incumbent is respectively willing to pay/receive to

[17]We thank an anonymous referee for pointing this argument out to us.

buy/grant access to the incumbent's network. The room for bargaining depends on the strength of the network externality; the incumbent's opportunity cost of granting the entrant access to its installed base grows with θ and, eventually, it becomes too large to be compensated by the increased profits of the entrant.

4.2 Compatibility through one-way converters

In this scenario each firm has the ability to build a one-way converter which grants one-way compatibility to the users of its product. As an example consider a software package that can read files created by other packages but cannot save in their format. More generally, *one-way compatibility happens when a component from one system works in the other, but the reverse is not true* (Katz and Shapiro, 1994). One-way converters allow one technology to obtain the network externalities accruing from the installed base of the other but not viceversa (David and Bunn, 1988).

Again, the incumbent chooses μ at the beginning of the game and can credibly commit to this decision. The rival chooses ϕ, namely whether or not to build the converter at time $t = 2$, having observed the incumbent's choices. Simple algebra shows that, for both firms, it is a dominant strategy to build the one-way converter; firms' profits shown in Section 3.1.2, can indeed be ranked as follows: $\pi^I_{c,x} > \pi^I_{i,x}$ and $\pi^E_{x,c} > \pi^E_{x,i}$, with $x = c, i$. This is not surprising because through a one-way adapter a firm is able to improve unilaterally the quality of its product by enlarging the size of its network.

Proposition 4. *For any possible value of θ, the only subgame perfect FE equilibrium involves both players building a converter (full compatibility: $\mu = 1$, $\phi = 1$).*

In this scenario, entry cannot be prevented by the incumbent and the entrant is on an equal footing with the incumbent, which loses its first mover advantage.

Corollary 1. *Entry of a one-way compatible entrant cannot be discouraged.*

4.3 Compatibility through one-way converters and disclosure of technical specifications

In this last case, the two firms have property rights on the technical specifications needed to build a one-way converter. Alternatively we can think of the case in which, in order to build a converter,

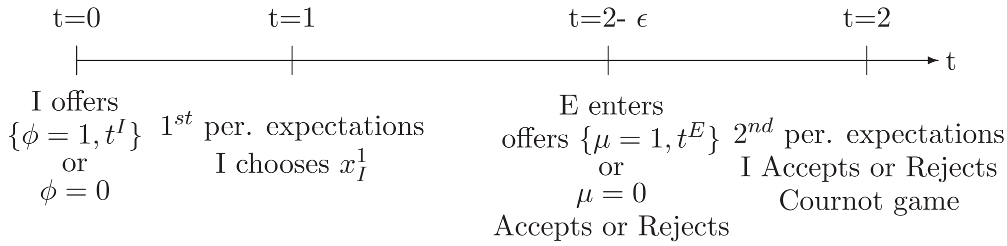

Figure 2: The time line with one-way converters and information disclosure

access is required to information that is privately owned by firms.

This implies that each firm has to decide whether or not to disclose such information to the rival, which in turn has to decide what to do with this information. Assume that when a firm offers the technical specifications required by the rival in order to build the adapter, the firm may charge a positive fee in the form of a lump-sum payment. The interpretation of this fee is clear: when a firm wants to build an adapter to make its technology compatible with that of the rival, it may be asked to pay a license fee for the use of the rival's proprietary technology.

Let us use t^I and t^E to denote the fee charged by the incumbent and the entrant respectively, when they offer the use of their technology.[18] The incumbent offers a pair $\left\{\phi = 1, t^I\right\}$ if it decides to disclose the information, or $\phi = 0$ otherwise. Similarly, in the case of information disclosure, the entrant offers a pair $\left\{\mu = 1, t^E\right\}$ or $\mu = 0$ otherwise. Once offered the information, each firm decides whether or not to build of the converter; we call this decision *accept* or *reject*. One-way compatibility ($\phi = 1$ and $\mu = 1$) is realised only upon acceptance by both firms of the rival's offer. The effect on the size of the relevant expected networks is then the same described in the previous section. The time line is represented in Figure 2.

The incumbent firm makes a commitment at the beginning of period 1 concerning disclosure of the technical information required by the entrant to build the converter. The same decision is taken by the entrant at the beginning of period 2 when the two firms decide, if given the opportunity by the rival, to build the converter before competing in quantities.

Market profits, gross of any fee paid or received, are those shown in Section 3.1.2; it is possible

[18]We do not impose a non negativity constraint on the fees. A negative fee implies an *invitation to use* the technology.

to see that the following inequalities hold:

$$\text{Incumbent:}\begin{cases} \pi^I_{x,c} < \pi^I_{x,i} \quad \forall x = i, c & \text{(A1)} \\ \pi^I_{c,x} > \pi^I_{i,x} \quad \forall x = i, c & \text{(B1)} \end{cases}$$

$$\text{Entrant:}\quad\begin{cases} \pi^E_{c,x} < \pi^E_{i,x} \quad \forall x = i, c & \text{(A2)} \\ \pi^E_{x,c} > \pi^E_{x,i} \quad \forall x = i, c & \text{(B2)} \end{cases}$$

In the absence of side payments, (A1) and (A2) imply that for both firms it is never profitable to disclose information about their technology. Furthermore (B1) and (B2) imply that both firms always find it optimal to build a one-way adapter to the rival's network when offered the required information. By revealing the technical details needed to build a one-way adapter, each firm allows the rival to improve the quality of its product without benefiting directly from it. It is therefore evident that both firms will never choose information disclosure without a payment and that, in the absence of side payments, the only subgame perfect equilibrium involves full incompatibility and, for sufficiently strong network effects, entry deterrence.

The following Proposition characterises the unique fulfilled expectations subgame perfect equilibrium of the game.

Proposition 5. *If $\theta < \theta^d$, then in the unique fulfilled expectations subgame perfect equilibrium of the information disclosure game: i) the entrant discloses its information and sets a positive fee $t^E \in \left[\pi^E_{i,i} - \pi^E_{c,i}, \pi^I_{c,i} - \pi^I_{i,i}\right]$; ii) the incumbent refuses disclosure, pays the fee t^E and builds the one-way converter. If $\theta \geq \theta^d$ the incumbent does not disclose information and entry is deterred.*

This is an asymmetric equilibrium in which the entrant *sells* access to its network to the incumbent at the licensing fee t^E; this fee is set at a level sufficiently low that the incumbent is willing to pay it: it can be shown that the profit loss for the entrant determined by the fall in market share due to the incumbent being one-way compatible, $\pi^E_{i,i} - \pi^E_{c,i}$, is less than the gain $\pi^I_{c,i} - \pi^I_{i,i}$, that the latter receives having access to the entrant's network in period 2. Because the entrant is one-way incompatible with the incumbent, as θ approaches θ^d, its market share shrinks (and so does t^E) until it eventually goes to zero and entry is deterred. This is an interesting and new result: to use a by now familiar expression in industrial organization, the entrant chooses a *puppy dog* strategy to soften competition from the incumbent by selling access to his network (Fudenberg and Tirole, 1984).

In the absence of side payments, our result closely replicates what was observed in the videogame industry when Nintendo denied Atari permission to include an adapter to enable Atari's users to play games written for Nintendo. In this case, the existence of property rights allowed an established technology to maintain its dominant position by preventing rivals from interconnecting with its installed base.

5 Socially optimal compatibility regimes

It is useful to conclude the paper with a comparison of the compatibility regimes selected by market players with those that a welfare maximising agent would choose, provided that firms were still free to compete in quantities. This is of crucial relevance to network industries, where the presence of network externalities not fully internalized by the firms may actually lead to market failures.

Social welfare is defined as the sum of consumer's and producer's surplus in the two periods. Social welfare depends on the compatibility regime represented by the values of parameters ϕ and μ, and on the strength of network externalities θ; the expressions for social welfare in the various compatibility scenarios are given in the last section of the technical appendix. Comparison of these expressions yields the following:

Proposition 6 (Socially optimal compatibility regimes)**.** *When entry cannot be deterred ($\theta < \theta^d$), welfare is maximised: i) with full compatibility ($\mu = 1$, $\phi = 1$) if $\theta < 0.27$; ii) with a one-way incompatible entrant ($\mu = 1$, $\phi = 0$) for $\theta \geq 0.27$. Deterrence is never socially optimal and for $\theta \geq \theta^d$, welfare is maximised with full compatibility.*

This proposition highlights two novel aspects of our analysis: the conflicting interests of early and late adopters and the strategic effect of compatibility. In a one period model like that of Katz and Shapiro (1985) the social desirability of compatibility derives from the increased network size that it induces. In our two period model, the presence of an installed base and the effect that the choice of the compatibility regime in period 2 produces on first period incumbent's level of output, generates conflicting interests between early and late adopters; moreover, the possibility of one-way compatibility regimes allows for a richer set of options. When $\theta < \theta^d$, entry always occurs in equilibrium whatever the compatibility choice made by the incumbent. From the social point of view, it is always preferable to have a compatible incumbent, $\mu = 1$, whereas the optimality of the compatibility of the entrant depends on the strength of the network effects. Since first period sales by a compatible incumbent (i.e. the installed base in the first period) are greater if the entrant is incompatible, early adopters prefer the entry of an incompatible firm which allows them to enjoy stronger network effects in the first period. By contrast, second period consumers strictly prefer full compatibility since it increases the second period relevant network. If the strength of network externalities is sufficiently low ($\theta < 0.27$), then the effect on second period consumers prevails and full compatibility is socially optimal. If $\theta \geq 0.27$, then the reverse holds and it is socially optimal to have a one-way incompatible entrant in the second period. The last part of the proposition shows that full compatibility is again socially optimal because, when the network effects are large enough, it serves the purpose of avoiding deterrence. From Proposition 6, the following Corollary derives easily:

Corollary 2 (Market failure)**.** *In the absence of side payments between firms:*

i) the game with a two-way converter supplied by the incumbent (game 1) and the game with one-way converters and information disclosure (game 3) always induce inefficient compatibility choices;

ii) the game with one-way converters (game 2) yields the socially desirable outcome for $\theta < 0.27$ *and* $\theta \geq \theta^d$*.*

When side payments are allowed:

i) game 1 yields the socially optimal compatibility regime for $\theta < 0.2$*;*

ii) game 3 yields the socially optimal compatibility regime for $\theta \in [0.27, \theta^d)$*.*

6 Conclusion

We have developed a simple model to study what we believe is an important aspect of competition in network industries which can account for the observed coexistence in a number of markets of different and incompatible technologies. Maintaining incompatibility with entrants is a strategic choice for an incumbent firm to protect its dominant position. With incompatibility, the installed base of consumers serves the same preemptive purpose as irreversible investment. In our model compatibility can be achieved via a converter and we have studied three different scenarios (two-way converter, one-way converters, one-way converters with property rights). In the absence of side payments, whenever an incumbent firm can prevent the entrant from being compatible, as in our first and third scenario, it will choose to do so. In the resulting equilibria, entry can be deterred for sufficiently strong network effects. Conversely, an incompatible entrant will always prefer to build an adapter (both one and two-way) because this will enable it to enjoy the benefits of the incumbent's installed base. When side payments are allowed, the possibility to share the larger potential surplus due to the increase in the willingness to pay of consumers yields interesting results. When the converter can only be two-way, the incumbent firm may have sufficient incentives to allow two-way compatibility if the network effects are not too strong; when the converters are one-way and technical information disclosure is required to allow the rival to build the adapter (the third scenario), we derive an equilibrium that is new in the literature and illustrates a novel strategy for an incompatible entrant: that is, allowing the incumbent access to its (smaller) network for a fee and sharing part of the increase in the potential surplus for the incumbent. We have finally discussed the welfare properties of the equilibria, showing that unless the regulatory authority intervenes to mandate the appropriate compatibility regime, strategic forces tend to lead to a socially inefficient compatibility outcome.

Appendix

Existence and uniqueness of second period fulfilled expectations Cournot equilibrium. Solving the maximisation problem (7) gives firms standard reaction curves:

$$x_I^2 = \frac{A - x_I^1 + \theta\,\hat{y}_I - x_E^2}{2}, \quad x_E^2 = \frac{A - x_I^1 + \theta\,\hat{y}_E - x_I^2}{2}. \tag{15}$$

To prove that the second period Cournot equilibrium with fulfilled expectations is unique and stable, we proceed in two stages. First, let us show that Assumption 1 is a sufficient condition for both the fulfilled expectations reactions curves to be negatively sloped and single valued. Imposing fulfilled expectations, namely $\hat{y}_I = x_I^1 + x_I^2 + \mu x_E^2$ and $\hat{y}_E = x_E^2 + \phi(x_I^1 + x_I^2)$, into expressions (15), the slopes of the reaction functions are simply:

$$\frac{dx_I^2}{dx_E^2} = \frac{\theta\mu - 1}{2-\theta}, \qquad \frac{dx_E^2}{dx_I^2} = \frac{\theta\phi - 1}{2-\theta},$$

which are both negative for $\theta < 1$. This is enough to verify that the reactions curves are also single valued. To guarantee existence and uniqueness of the second period equilibrium, we can invoke Szidarowsky and Yakowitz (1977) and show that the reaction functions are decreasing in the total industry output. From the reaction functions (15):

$$x_I^2 = A - x_I^1 - x_{tot} + \theta \hat{y}_I \quad \text{and} \quad x_E^2 = A - x_I^1 - x_{tot} + \theta \hat{y}_E,$$

where $x_{tot} = x_I^2 + x_E^2$. For any $\theta < 1$, both these expressions define a continuous function $x_i^2(x_{tot})$ which is decreasing in x_{tot}. Therefore also the sum $x_I^2 + x_E^2$ is continuous and decreasing. The FEE is given by the level of output such that $x_{tot} = \sum_i x_i^2(x_{tot})$. The Brower's fixed point theorem guarantees the existence of the equilibrium while the condition $x_i^2(x_{tot})' < 0$ is sufficient for establishing uniqueness.

■

Existence and uniqueness of first period FEE. From expression (12), with fulfilled expectations the equilibrium level of first period sales is the solution to $x_I^1 = x_I^1(\hat{x}_I^1)$ where (12) can be conceived as a mapping of sales expectations into actual ones. FEE then defines a fixed point of the function $x_I^1(\hat{x}_I^1)$. Since $x_I^1(\hat{x}_I^1)$ is a linear function of $\hat{x}_I^1$, then to prove the existence, uniqueness and stability of the equilibrium it is sufficient to verify that

$$\frac{dx_I^1(\hat{x}_I^1)}{d\hat{x}_I^1} < 1. \tag{16}$$

Differentiating expression (12):

$$\frac{dx_I^1}{d\hat{x}_I^1} = \frac{-3((-1+\mu\phi)\theta^2 + (4-\phi-\mu)\theta - 3)\theta}{(\phi^2\mu - \phi + 2 - 2\,\mu\phi)\theta^3 + (2\mu - 9\mu\phi - \phi^2 + 4 + 4\phi)\theta^2 + (9\phi - 33 + 8\mu)\theta + 22}.$$

This expression provides the slope of the mapping $x_I^1 = x_I^1(\hat{x}_I^1)$ as a function of θ, given the compatibility parameters $\phi = \{0,1\}$ and $\mu = \{0,1\}$. It is easy to verify that condition (16) is met for $\theta < 1$ for all the combinations of the compatibility parameters except in the full incompatibility case ($\mu = 0, \phi = 0$). In this case, condition (16) is satisfied for $\theta < 0.704$, which is the lower level of the upper bound $\bar{\theta}$.
Finally, by setting $x_I^1 = \hat{x}_I^1$, the first period FEE output given in (13) can be easily derived.

■

Proof of Proposition 1. In order to establish when the incumbent deters entry, we need to study under which conditions the optimal level of first period output x_I^1 is greater than x_I^d. Using expressions (12) and (14) to compute the differences $\Delta\,|_{\phi=1} = x_I^1 - x_I^d$ and $\Delta\,|_{\phi=0} = x_I^1 - x_I^d$; with simple manipulations we obtain:

$$\Delta\,|_{\phi=1} = \frac{A\,(\theta-4)\left((\mu-1)\,\theta^2 + (3-\mu)\,\theta - 3\right)}{(\theta-1)\left((2\,\mu-2)\,\theta^3 + (16-10\,\mu)\,\theta^2 + (8\,\mu-33)\,\theta + 22\right)}, \tag{17}$$

$$\Delta\,|_{\phi=0} = \frac{A\left(\theta^2 - 13\,\theta + 4\right)\left(3 + \theta^2 + \theta\,\mu - 4\,\theta\right)}{-22 - 16\,\theta^2 + 42\,\theta - 8\,\theta\,\mu + \theta^2\mu + \theta^3}. \tag{18}$$

We want to determine the sign of each of the two expressions. Let us start from (17). The numerator is always positive; the sign of denominator is negative for θ=0, still negative for θ approaching 1, and since it is strictly convex in θ, the sign remains negative over the interval $[0,1)$. Therefore the sign of (17) is negative. This shows that with a compatible entrant ($\phi = 1$) entry is never deterred in the FEE equilibrium.

Now consider (18); to determine the sign of this expression it is useful to consider the two cases $\mu = 1$ and $\mu = 0$ separately. With $\mu = 1$, (18) becomes:

$$\frac{A\left(\theta^2 - 13\,\theta + 4\right)\left(3 + \theta^2 - 3\,\theta\right)}{-22 - 15\,\theta^2 + 34\,\theta + \theta^3}.$$

The denominator is negative both for θ=0 and θ=1 and its first derivative is strictly positive in θ, thus implying that the denominator is always negative. The numerator is positive for θ=0 and negative for θ=1, the second derivative is always positive in $\theta \in [0, 1)$. This is sufficient to prove that there is only one value of θ such that the numerator is zero. This happens for $\theta = 0.315 \equiv \theta^d$. Therefore, the sign of (18) when $\mu = 1$ is negative for $\theta < \theta^d$ and positive thereafter.

With $\mu = 0$, (18) becomes:

$$\frac{A\left(\theta^2 - 13\,\theta + 4\right)\left(3 + \theta^2 - 3\,\theta\right)}{-22 - 16\,\theta^2 + 42\,\theta + \theta^3}.$$

The numerator is the same as in the previous case. As for the denominator, it is easy to check that it is always negative in the relevant range of θ. Therefore the result is the same as before. We can finally conclude that $\Delta\,|_{\phi=0} \geq 0$ only if $\theta \geq \theta^d$, which ends the proof of the first part of the proposition.

To prove the second part we need to show that the output produced by the incumbent when it acts as a pure monopoly, x^1_{mon}, in the first period is not sufficient to deter entry for $\theta < 0.394$. To do this we compute the optimal production plan for the two periods under the assumption that the incumbent is the only active firm. Second period monopoly output contingent on x^1_I is the same as in the duopoly case,[19] while the first period output is different and is given by $x^1_{mon} = \frac{4A}{\theta^2 - 9\theta + 10}$.

From the comparison of x^1_{mon} with x^d_I, it is straightforward to verify that $x^1_{mon} \geq x^d_I$ if and only if $\theta \geq 0.394$.

■

Proof of Proposition 5. Firms' profits in the various possible compatibility scenarios are given in Section 3.1.2; simple but tedious algebraic manipulations show that the following profit rankings apply:

$$\pi^I_{c,i} > \pi^I_{i,i} > \pi^I_{c,c} > \pi^I_{i,c}, \quad \text{and} \quad \pi^E_{i,c} > \pi^E_{c,c} > \pi^E_{i,i} > \pi^E_{c,i},$$

where $\pi^H_{x,y}$ is the profit of firm H, gross of the license fee received from or paid to the rival, under the compatibility regime x, y, with $x, y = c, i$.

As we have discussed in the text, in the absence of licence fees, the subgame perfect FEE equilibrium implies full incompatibility and, for $\theta \geq \theta^d$, entry deterrence. With side payments the proof is more articulated. To simplify the extensive form representation of the game, note that the two offers $\left\{\mu = 1, t^E\right\}$ and $\mu = 0$ are equivalent if t^E is high enough: there always exists a fee high enough to induce the incumbent to reject the offer. Similarly $\left\{\phi = 1, t^I\right\}$ and $\phi = 0$ are equivalent for high enough t^I. This observation allows us to

[19] Formally, it is equal to $x^2_{mon} = \frac{A - (1-\theta)x^1_{mon}}{2-\theta}$.

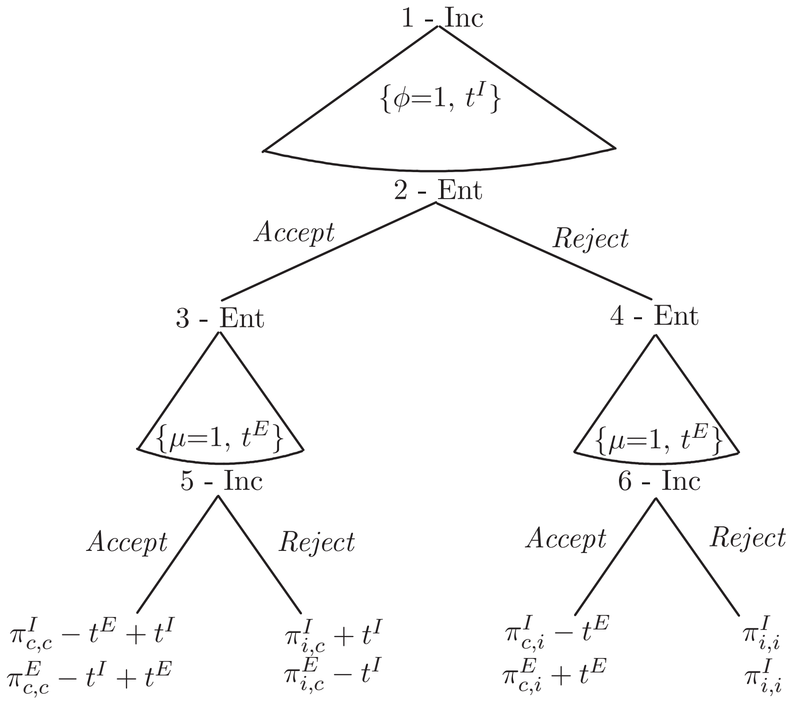

Figure 3: The game tree with one-way converters and information disclosure

consider the offer of the two firms as one dimensional: a price t^j, $j = I, E$ that induces the rival firm either to accept or to reject. The game tree is represented in Figure 3.

Let us proceed by backward induction and consider the choice of the incumbent firm at nodes 5 and 6. In both nodes the incumbent will accept the offer if the level of t^E is not too high. At node 5 the reservation price for the incumbent is $t^E < \pi^I_{c,c} - \pi^I_{i,c} = \underline{\Delta}^I$, whereas at node 6 the reservation price is $t^E < \pi^I_{c,i} - \pi^I_{i,i} = \overline{\Delta}^I$. Note that $\underline{\Delta}^I > \overline{\Delta}^I > 0$. At the nodes 3 and 4 the entrant has to decide the level of t^E; at node 3 the entrant finds it optimal to set a t^E that is acceptable to the incumbent if and only if the following holds: $t^E > \pi^E_{i,c} - \pi^E_{c,c} = \overline{\Delta}^E$, whereas at node 4 the following condition must be satisfied: $t^E > \pi^E_{i,i} - \pi^E_{c,i} = \underline{\Delta}^E$. Again, note that $0 < \underline{\Delta}^E < \overline{\Delta}^E$.

Since $\underline{\Delta}^I > \overline{\Delta}^E > 0$ and $0 < \underline{\Delta}^E < \overline{\Delta}^I$ there exists a t^E such that the entrant is willing to offer it (at nodes 3 and 4 respectively) and the incumbent is willing to accept it (at nodes 5 and 6 respectively). At node 2 the entrant is willing to accept the incumbent's offer if and only if $\pi^E_{c,c} + t^E - t^I \geq \pi^E_{c,i} + t^E$ which imposes an upper bound on $t^I \leq \pi^E_{c,c} - \pi^E_{c,i}$ (C1). Finally at node 1 the incumbent chooses the level of t^I; it will offer a t^I that is acceptable to the entrant if and only if $\pi^I_{c,c} - t^E + t^I \geq \pi^I_{c,i} - t^E$ or, equivalently, $t^I \geq \pi^I_{c,i} - \pi^I_{c,c}$ (C2). Conditions (C1) and (C2) are mutually exclusive. Therefore there does not exist a t^I that can satisfy both, and the incumbent makes an offer that is refused by the entrant. In the only subgame perfect equilibrium, the incumbent makes an offer that is rejected by the entrant, who makes an offer that is accepted by the incumbent.

■

Social Welfare. Social welfare is defined as the sum of consumers' and producers' surpluses in the two periods; it depends on the compatibility parameters ϕ and μ and on the strength of network externalities θ:

$$W(\phi,\mu;\theta) = CS^1(\phi,\mu;\theta) + CS^2(\phi,\mu;\theta) + \sum_i \pi^i(\phi,\mu;\theta), \qquad i = I, E \tag{19}$$

where CS^i denotes the surplus enjoyed by period i consumers.

Consider first period consumers. Their total surplus is the sum of the surplus derived over both periods. According to (2), the total surplus for the individual of type r is

$$CS^1(r) = r + V(\hat{x}_I^1) - p_I^1 + r + V(\hat{y}_I), \tag{20}$$

where p_I^1 is the price paid in the first period which, according to (5), depends on the price in the second period, p_I^2. Replacing (5) and (6) into (20) and rearranging, the total surplus for the individual of type r when he joins the incumbent network in the first period reduces to $CS^1(r) = 2(r - A + x_I^1) + (x_I^2 + x_E^2)$. At the FEE, only those consumers with r bigger than $A - x_I$ purchase the good in the first period. Integrating over all consumers who do join the network in the first period we derive the consumers' surplus:

$$CS^1 = \int_{A-x_I}^{A} [2(\gamma - A + x_I^1) + (x_I^2 + x_E^2)]d\gamma = (x_I^1)^2 + x_I^1(x_I^2 + x_E^2),$$

where the x's represent the fulfilled expectations firms' output.

Consider second period consumers; the surplus enjoyed by the type r individual when purchasing from firm i in the second period is simply given by:

$$CS_i^2(r) = r + V(\hat{y}_i) - p_i^2 = r - A + x_I^1 + x_I^2 + x_E^2, \qquad i = I, E$$

where the last expression has been obtained using (6). In the second period, only those consumers with r bigger than $A - x_I - x_I^2 - x_E^2$ purchase the good, provided that those with $r > A - x_I$ have already joined the network in the first period; therefore, total second period consumers' surplus is:

$$CS^2 = \int_{A-x_I-x_I^2-x_E^2}^{A-x_I} [\gamma - A + x_I^1 + x_I^2 + x_E^2]d\gamma = \frac{(x_I^2 + x_E^2)^2}{2},$$

Similarly, we can compute the surplus when entry is deterred/blockaded by the incumbent; these are simply given by[20] $CS_{mon}^1 = (x_I^1)^2 + x_I^1 x_I^2$ and $CS_{mon}^2 = \frac{(x_I^2)^2}{2}$, respectively.

[20] For the sake of brevity, we omit the algebra, which is available upon request.

The FEE quantities sold in both periods are known. By substituting them into the above expressions, we compute the expressions of the welfare function (19) for all the scenarios considered: full compatibility, full incompatibility, one-way compatibility and entry deterrence/blockaded; formally:

$$\mathrm{W}_{c,\,c} = \frac{1}{2}\,\frac{A^2\,(808 - 16\,\theta^3 + 192\,\theta^2 - 696\,\theta)}{(22 - 25\,\theta + 6\,\theta^2)^2},$$

$$\mathrm{W}_{c,\,i} = \frac{1}{2}\,\frac{A^2\,(808 + 34\,\theta^4 + 12\,\theta^5 + 1074\,\theta^2 - 1424\,\theta - 236\,\theta^3)}{(22 + 15\,\theta^2 - 34\,\theta - \theta^3)^2},$$

$$\mathrm{W}_{i,\,c} = \frac{1}{2}\,\frac{A^2\,(808 - 2\,\theta^5 + 932\,\theta^2 + 39\,\theta^4 - 1416\,\theta - 280\,\theta^3)}{(22 + 16\,\theta^2 - 33\,\theta - 2\,\theta^3)^2},$$

$$\mathrm{W}_{i,\,i} = \frac{1}{2}\,\frac{A^2\,(808 + 1798\,\theta^2 - 326\,\theta^3 + 4\,\theta^5 - 2144\,\theta + 31\,\theta^4)}{(22 + 16\,\theta^2 - 42\,\theta - \theta^3)^2},$$

$$\mathrm{W}^d = \begin{cases} A^2\left(1 + \theta - \frac{3}{2}\,\theta^2 + \theta^3\right) & \text{if} \quad \theta \in [0.315, 0.394] \\ \dfrac{1}{2}\,\dfrac{(11\,\theta^2 - 66\,\theta + 131)\,A^2}{(\theta^2 - 9\,\theta + 10)^2} & \text{if} \quad \theta \in (0.394, \bar{\theta}] \end{cases}$$

where W^d represents welfare when the incumbent deters entry or when entry is blockaded. Proposition 6 can be proved through simple comparison of the welfare levels found for the different compatibility scenarios. The algebra is extremely tedious; for the sake of brevity, we omit the details but we leave the formal proof available upon request for the authors.

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