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THE EVOLUTION OF MARKETS UNDER ENTRY AND STANDARDS REGULATION – THE CASE OF GLOBAL MOBILE TELECOMMUNICATIONS

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The evolution of markets under entry and standards regulation – the case of global mobile telecommunications*

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Abstract:

We analyze the effects of government policies on the evolution of an industry, the global mobile telecommunications market. (i) We find a relatively slow diffusion convergence between countries. This follows partly from regulatory delay in issuing first licenses, yet persisting initial cross-country differences also contribute to a lack of convergence. (ii) Introducing competition has a strong immediate impact on diffusion, but a weak impact afterwards; sequential entry is preceded by pre-emptive behavior by incumbents. This is consistent with the presence of consumer switching costs. (iii) Setting a single technological standard accelerates the diffusion of analogue technologies considerably; for digital technologies it is too early to draw reliable conclusions, yet the available evidence suggests that setting single standards has similar beneficial effects.

Keywords: technology diffusion, entry regulation, regulatory delay, switching costs, standards and competing systems, network externalities, mobile telecommunications.

JEL classification numbers: L1, L96, O3.

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1. Introduction

In most emerging industries governments intervene through various types of regulation, thereby affection the diffusion of new technologies. Because of the drastic technological changes, there is usually little consensus on optimal policies to be followed. A first issue is whether and how entry by new firms should be regulated, and what the timing of entry should be. A second issue is whether it is in the public interest that the policy maker sets a technological standard, or whether this decision should be left to the market through competition among systems. Another way of putting this question is whether standards create markets or markets create standards. Apart from unresolved theoretical issues, there is little empirical work on the effects of public policy intervention on the diffusion of new technologies. The aim of this paper is to assess empirically the effects of entry regulation and standard-setting on the evolution of a specific industry, the worldwide cellular mobile telecommunications services industry.

There is an extensive theoretical literature on the relationship between market structure, entry and the diffusion of innovation. In telecommunications, it has been argued that competition creates additional incentives to reduce costs, to innovate and to eliminate distorted prices (Laffont and Tirole, 2000). While there has been some empirical work on the role of market structure and competition in the diffusion of innovation, the effects of the timing of entry have not been systematically considered. Important empirical issues on entry in telecommunications are: the impact of regulatory delay in issuing first entry licenses on the diffusion of innovation; the pre-emptive, immediate and long-term effects of additional entry licenses on the diffusion of innovation; and the distinction between simultaneous versus sequential entry.

The theoretical literature on technological standards versus competing systems in industries with network effects has grown very large and some convergence in the conclusions seems to emerge (Shapiro and Varian, 1999). A system is subject to network externalities if consumers value a system more the more users adopt it. With standards the market should therefore grow faster. For instance, standards tend to benefit consumers as they reduce their search and switching costs. But there is also the risk that a selected standard is not the most efficient one and that it becomes difficult to switch or develop a better one. Moreover, there are several industries where different incompatible systems coexist and other cases where market forces push one system to take the whole market establishing itself as the standard (e.g. the VHS system for video recorders). Definite answers on market outcomes delicately depend on the market and technology parameters involved. Despite the extensive theoretical literature, there exists no empirical work that compares the effect of imposing standards on the diffusion of a new technology with the effect of allowing multiple systems to compete.[1]

The cellular mobile telecommunications industry offers an interesting opportunity to make a comparative analysis, since countries have followed quite heterogeneous and changing policies both regarding entry regulation and setting standards. Our data set covers the entire evolution of the cellular mobile industry (1981-1997)[2] for most countries in the worlds. There is an increasing empirical IO literature on the diffusion of cellular mobile telecommunications. Most studies have considered the cellular mobile industry in individual or a restricted number of countries, focusing on market conduct (Parker and Röller, 1997; Nattermann, 1999), or on the role of country characteristics (Dekimpe, Parker and Sarvary 1998). The finding that firms have market power is well established, but this has not yet been linked up with the diffusion literature The novelty of this paper is that it establishes a link between the effects of the design of market structure, i.e. entry regulation and setting of standard, on competition and diffusion.

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[1] For an analysis of the presence of network effects, see Saloner and Shepard (1995). They do not directly

Gruber and Verboven (2000) looked at the effects of competition on diffusion by looking at E.U. countries, emphasizing the importance of the capacity increase due to the transition from the analogue to digital technology. This paper complements these findings in various respects; (1) by analyzing the role of regulatory delay in issuing first entry licenses on the speed of diffusion convergence between countries; (2) by considering the pre-emptive, immediate and long-term effects from competition on the diffusion of innovation, and distinguishing between simultaneous versus sequential entry; (3) by looking at technology standards versus competing systems; (4) by extending coverage to a world-wide data set of 140 countries with a substantial heterogeneity in policies regarding entry regulation and standards.

The paper is arranged as follows. Section 2 provides a brief description of the most relevant technological aspects of cellular systems. Section 3 describes the public policies regarding entry licensing and technology standards in the various countries. Section 4 describes the econometric model. Section 5 presents and discusses the empirical results on the effects of entry regulation and standards on the evolution of the industry. Section 6 concludes and suggests implications for public policy.

2. The choice of the technological system

Mobile telecommunications use radio waves, instead of wires, to connect users[3]. The available portion of the radio frequencies in the overall spectrum is limited both by technology and regulation. The earliest applications for mobile communications date back to the 1920s. Early mobile telecommunications systems had very limited capacity since they

compare competing systems with single standards.

[2] The exception is Japan, where cellular mobile telecommunications were already introduced in 1979.

[3] For a description of each of technological aspects see Calhoun (1988) Garg and Wilkes (1996) and Rappaport (1996).

made use of the spectrum in a very inefficient way. The more efficient cellular concept of mobile telecommunications was developed during the 1960s. The system is called "cellular" because the era to be served is divided into cells with an antenna in the middle. This design, coupled with sophisticated electronics, allowed for more efficient use of spectrum and therefore to accommodate a much larger number of users for a given range of spectrum. Because of regulatory delays, cellular systems were deployed only by the beginning of the 1980s (Calhoun, 1988).

One may distinguish between two types of cellular technologies according to the way in which the signals are transmitted: the analogue (or first generation) and the digital (or second generation) technology starting at the beginning of the 1990s. The digital technology improved capacity by about 3 to 6 times over analogue technology. Digital technology has several additional advantages too, such as less noise in operation and enhanced privacy.

Various systems were developed for both the analogue and digital cellular technology. They mainly differ in their ability to use the spectrum efficiently. Seven analogue systems found application worldwide, compared to four digital systems. The larger number of analogue systems in the early days of the cellular industry may be explained by the fact that most countries viewed cellular telecommunications as just an additional new business of the state-owned telecommunications monopoly. Thus, the development of the cellular network was a means of honing the innovative capabilities of national equipment suppliers. It turned out that the most successful systems (in terms of the number of adopting countries) emerged when the domestic market was sufficiently large (e.g. analogue AMPS for the U.S.) or where there was a common standard across countries (analogue NMT for Scandinavian countries or digital GSM for Europe).

3. Government licensing policies

Government licensing policy in mobile telecommunications has various dimensions. First, the government needs to decide whether to set a single national (or international) standard, or whether to allow multiple technological systems to compete. Second, the government has to decide to how many firms will receive a license. This also involves an important decision with respect to the timing of first and additional licenses. Third, the government needs to decide how to grant licenses. In the early days of mobile telecommunications, licenses were often granted on a first-come-first-serve basis. With the introduction of the cellular technology, the first licenses were frequently granted automatically to the incumbent fixed operators. Additional licenses were either granted through an auction, or through an administrative tender procedure (or "beauty contest"), possibly including a license fee.

In our study we focus on the first and the second dimensions of the licensing policies: a single standard versus competing systems; and timing of first and additional licenses. The room for discretionary policy is limited by the available spectrum capacity and by the technological options. The policy decisions may be described by a 2×2 policy matrix as follows. The columns denote the number of countries that opted for a single standard or for multiple competing systems. The rows denote the number of countries that admitted one monopoly operator or competing operators. This policy matrix will be used in our discussion of the government licensing policies in the subsections below.

3.1. Multiple systems or single standards

In markets with network externalities there are both advantages and disadvantages to having competing systems. The presence of (strong) network externalities typically leads to "tipping" markets, where the winning technology takes the whole market. Should the government intervene in this race by imposing a single standard *ex ante*? Or should the markets decide themselves on which standard will eventually "win"? The theoretical literature does not provide an unambiguous answer to these questions (for an overview, see Katz and Shapiro, 1994). Advocates of government intervention argue that imposing a standard makes it possible to realize network externalities faster and reduces the technological uncertainty among consumers. Advocates of free markets point out that system competition is the best guarantee to promote technological progress and to develop even better technological systems. It also reduces the risk of being locked in into an inferior technology promoted by the government[4]. A counter argument is that free markets may also lead to lock in into inferior outcomes, thereby necessitating government intervention to cope with this network externality[5].

In practice, Varian and Shapiro (1988) argue that network externalities in the cellular mobile industry are "strong, but not overwhelming". For example, even if consumers are locked in into one system, they can switch to other systems at a discount in exchange for signing service contracts. They conclude that the market is not especially prone to tipping. And indeed, in none of the cases where competition between systems was allowed there was a system that eventually cornered the market fully and became the de facto standard (e.g. the U.S. digital cellular market still supports three systems).

What is the relative importance of competing systems versus standards for cellular telecommunications? Table 1 shows that of the 118 countries that adopted an analogue cellular system, 105 opted for a single standard, and 13 for competing standards. A quite similar picture obtains for the countries that adopted a digital system. Of the 87 countries, 79

[4] An example is high definition television in Japan, where the government promoted an analogue standard neglecting the fact that the worldwide evolution would be toward digital technology (Shapiro and Varian, 1999).

opted for a single standard, and 8 for competing standards. Thus there is a fairly constant fraction of countries (about 10%) that adopts multiple systems.

(insert Table 1 about here)

3.2. The timing and the number of licenses

Countries have been quite heterogeneous in their decisions and timing to issue first and additional licenses. Table 1 shows that of the 118 countries that adopted an analogue cellular system, 88 countries had chosen for a monopoly (of which 83 with a single standard and 5 with multiple systems) and 30 countries had chosen an oligopoly. This relationship is reversed for the digital technology. Of the 87 countries, only 39 have a monopoly, whereas 48 have an oligopoly. This indicates a worldwide trend towards oligopoly with the introduction of the digital technology.

An explanation for this pattern relates to the differences in capacities during analogue and the digital periods. The countries that introduce first licenses early have a strong preference for a wide diffusion of the new technology. Yet during the early years of the analogue technology capacity was still very much constrained, so that the countries would gain little from introducing competition. With the introduction of the digital technology, capacity expanded drastically. The early moving countries then had much to gain from introducing competition immediately. In contrast, the late-coming countries, with a presumably lower preference for a widespread diffusion, had a lower incentive to introduce competition.

Capacity thus seems to be a first crucial factor in explaining the effects of competition on the diffusion of mobile penetration. When capacity is constrained, as under the analogue technology (especially during the early years), the effects of competition on mobile

[5] The typical example reported in the literature is the QUERTY keyboard winning over the allegedly superior Dvorak keyboard. For a critique of the empirical relevance of network externalities, see Liebowitz and Margolis

penetration are likely to be modest. The effects of competition are potentially much larger under the digital technology when capacity constraints are relaxed.

In addition to capacity, consumer switching costs are a potential determinant of the competition effects in the mobile industry (see e.g. Valletti and Cave, 1998). For example, mobile operators frequently offer long-term contracts to consumers, thereby artificially creating lock-in[6]. In a one-period context, switching costs (like product differentiation) tend to soften competition between operators. In a dynamic setting, switching costs may induce firms to compete more aggressively for market share during the early phases of competition. The presence of switching costs gives rise to some testable predictions. First, switching costs can explain why competition effects are stronger during the first year than afterwards. Second, switching costs may explain the presence of pre-emptive behavior by an incumbent if entry is sequential. This may be done, for example, through limit pricing (charging lower prices than a monopolist would) or by following aggressive marketing campaigns. Limit pricing may be explained by a desire to build a strong installed base to exploit market power. However, "limit overpricing" may also occur, if it is more important to induce soft competition by a future entrant. Limit pricing is more likely if switching costs are present but not too large, and if there is a significant growth of new consumers.[7]

(1999).

[6] As mentioned before, switching costs are further enhanced when there are multiple systems. Indeed a customer who wants to switch to a new supplier of mobile services using a different system has to invest also into a new handset that is compatible with this system.

[7] See Klemperer (1995) for a model of sequential entry in the presence of switching costs. Van De Wielle and Verboven (1999) compare simultaneous and sequential entry in a model with switching costs. Gruber (1999) provides evidence on switching costs by comparing market shares of mobile operators under simultaneous and sequential entry.

4. The econometric model of diffusion

4.1. A logistic model of diffusion

The evolution of the market is based on a logistic model of technology diffusion; see Geroski (2000) for a recent overview of the literature on technology diffusion. Let y_{it} denote the number of agents that have adopted the new technology in country i at time t; let y_{it}^* denote the total number of potential adopters. The fraction of the total number of potential adopters in country i that have adopted before time t follows the logistic distribution function:

$$\frac{y_{it}}{y_{it}^*} = \frac{1}{1 + \exp(-a_{it} - b_{it}t)}. \qquad (1)$$

The variable a_{it} in (1) is a location or "timing" variable. It shifts the diffusion function forwards or backwards, without affecting the shape of the function otherwise. For example, when a_{it} is very high, we may say that country i at time t is very "advanced" in its adoption rate. The variable b_{it} is a measure of the diffusion growth. This can be verified from differentiating (1) with respect to t, and rearranging:

$$\frac{dy_{it}}{dt}\frac{1}{y_{it}} = b_{it}\frac{y_{it}^* - y_{it}}{y_{it}^*}.$$

This implies that b_{it} equals the growth rate in the number of adopters at time t, relative to the fraction of adopters that have not yet adopted at time t. Equivalently, this says that the number of new adopters at time t, relative to the fraction of adopters that have not yet adopted at time t, is a linear function of the total number of consumers that have already adopted at time t. This reflects the epidemic character of the logistic diffusion model.

It can be verified that the second derivative of (1) is positive for $y_{it}/y_{it}^* < 1/2$, and negative if the reverse holds. The diffusion of the number adopters thus follows an S-shaped pattern, with a maximum diffusion speed reached when half of the total number of potential adopters has effectively adopted the new technology.

In our econometric analysis we transform equation (1) as follows:

$$\log\left(\frac{y_{it}}{y_{it}^{*}-y_{it}}\right) \equiv z_{it} = a_{it} + b_{it}t \,. \tag{2}$$

The dependent variable, z_{it}, is the logarithm of total number of adopters relative to the number of potential adopters that have not yet adopted. We now specify the three essential determinants for the diffusion of mobile telecommunication services: the total number of potential adopters, y_{it}^*; the location variable, a_{it}; and the growth variable b_{it}.

The total number of potential adopters, y_{it}^*.

Assume that y_{it}^* evolves proportionally to the total population, POP_{it}:

$$y_{it}^{*} = \gamma_i POP_{it}, \tag{3}$$

where γ_i is the proportion of the population in country i that eventually will adopt a mobile phone. In principle, γ_i can be estimated as fixed effects for each country. In practice, this is difficult, since most countries are still at the early stages of diffusion. Gruber and Verboven (2000) resolved this problem by pooling the data, and estimating a parameter γ, common for all countries. This facilitates estimation because one can exploit information from both countries in early and in more mature stages of diffusion. This approach may be justified in their study, which considered the relatively homogeneous group of E.U. countries. In our present study, which covers a heterogeneous set of almost all countries in the world, this approach is harder to justify. A more flexible approach would be to allow the parameter γ to differ across certain groups of countries, according to various economic and social determinants, such as income, the level of education or urbanisation. In practice, this approach proved difficult, essentially because within each group only few countries had reached more mature stages of diffusion.[8]

Dekimpe, Parker and Sarvary (1998) followed an alternative approach. They treat the total number of potential adopters as a "known" parameter. More specifically, based on industry interviews, they specify the total number of potential adopters as: "the percentage of the literate people living in urban areas having a sufficient income to afford basic telephone service". Our approach is in a similar spirit: we treat the fractions γ_i as known parameters, dependent on urbanization and economic development.[9] The empirical results were robust with respect to alternative assumptions.[10]

The location and growth variables a_{it} and b_{it}.

The location variable a_{it} and the growth variable b_{it} in (2) are specified in a general form as:

$$a_{it} = \alpha_i^0 + \sum_{j=1}^{J} \alpha^j D_{it}^j + x_{it}\alpha$$

[8] The problems were of two types. First, convergence was often difficult to obtain, since the model is nonlinear and the parameter γ often causes the term within the logarithm to become negative. Second, if convergence was reached, the standard errors were quite high, essentially saying the data are at present uninformative about the total market potential.

[9] Another important determinant for diffusion not explicitly included is equipment prices. For instance Garrard (1998) reports that the first cellular user terminals (which because of their heavy weight were actually not hand held but car-mounted) cost US$ 3000 at the beginning of the 1980s. Prices declined rapidly, as did weight. Ten years later, a handset was already available at US$ 200. While the lightest handset weighted 850 grams in 1985, this was reduced to less than 100 gram at the end of the 1990s. There are relatively few equipment suppliers worldwide and price decline of equipment occurred uniformly on a worldwide scale. Price levels may differ across countries mainly because of tax and tariff reasons. The model takes account of these effects through fixed effects and the time trend.

[10] In particular, we experimented with alternative values for γ, common across countries. We also allowed γ to be specific to the income class of the country, and to depend on the degree of urbanization. The empirical results are robust under these alternative assumptions. Intuitively, this is because most countries are far away from reaching full adoption. The empirical results are based on γ=.45, which was the estimate obtained for a restricted specification, excluding all variables but the time trend.

$$b_{it} = \beta_i^0 + \sum_{j=1}^{J} \beta^j D_{it}^j + x_{it}\beta . \qquad (4)$$

The parameters α_i^0 and β_i^0 are country-specific location and growth effects. The variables D_{it}^j are dummy variables to capture the effect of certain events j. More specifically, let T_i^j denote the time of a certain event j in country i, e.g. the introduction of competition in country i. The dummy variable D_{it}^j then equals zero for $t < T_i^j$, and equals one for $t \geq T_i^j$. The parameters α^j and β^j measure the effect of event j on the timing and growth variables; they are assumed to be the same across countries. The vector x_{it} includes continuous variables affecting the location or growth variables, e.g. per capita income.

Specification (4) allows an event j to have an effect on both the location and growth variable in an unrestricted way. Most of the empirical literature implicitly imposes structure on the specification by allowing the variable to enter only in the location or in the speed variable. We instead propose a more systematic approach. We impose and test the restriction that there is no discontinuous jump or fall in the number of adopters after event j takes place; there can thus only be a smooth acceleration or deceleration after event j. More formally, we impose the restriction that the adoption level at the time of introduction of event j, i.e. at T_i^j, is equal to the adoption level slightly before the time of introduction of event j, i.e. at $T_i^j - \varepsilon$ (with ε small). Since at T_i^j, $D_{it}^j = 1$, and at $T_i^j - \varepsilon$, $D_{it}^j = 0$, this condition implies that:

$$\alpha_i^0 + \alpha^j + \sum_{k \neq j} \alpha^k D_{it}^k + x_{it}\alpha + \left(\beta_i^0 + \beta^j + \sum_{k \neq j} \beta^k D_{it}^k + x_{it}\beta \right) T_i^j$$

$$= \qquad \alpha_i^0 + \sum_{k \neq j} \alpha^k D_{it}^k + x_{it}\alpha + \left(\beta_i^0 + \sum_{k \neq j} \beta^k D_{it}^k + x_{it}\beta \right) T_i^j ,$$

which simplifies to:

$$\alpha^j = -\beta^j T_i^j . \tag{5}$$

Substituting (4), using restriction (5), into the transformed diffusion equation (2), we obtain:

$$z_{it} = \alpha_i^0 + x_{it}\alpha + \left(\beta_i^0 + x_{it}\beta\right)t + \sum_{j=1}^{J} \beta^j D_{it}^j \left(t - T_i^j\right). \tag{6}$$

To test restriction (5), one may first estimate (6) after including α^k as in the unrestricted equation, and apply standard t-tests or F-tests on the (joint) significance of the α^k.

4.2. Empirical specification

We now specify the model used to analyze the role of the timing of first and additional entry licenses, the effects of standards regulation, and country characteristics.

The timing of first entry licenses.

The policy relevance of the timing of first entry licenses depends on the speed of diffusion convergence between early and late-coming countries. If convergence between early and late-coming countries occurs slowly, then regulatory delay has long persisting consequences and the timing of first entry licenses becomes a very central part of regulatory policy. If convergence is fast, then the timing of first entry licenses may be of secondary importance to policy makers. The speed of convergence, or the extent of catching-up, may depend on various factors, such as declining investment costs through calendar time, international learning spillovers, etc...

To assess the speed of convergence, we analyze the relation between the fixed effects, α_i^0 and β_i^0. For example, an early country (with a typically high α_i^0) may have a lower growth (β_i^0) than a late-coming country (with a low α_i^0). If this is consistently the case, then there is catching-up by latecomers, or international convergence. One simple way to incorporate a catching-up effect is by imposing the following relationship between α_i^0 and β_i^0:

$$\beta_i^0 = \beta^0 - \lambda\alpha_i^0. \tag{7}$$

If λ is positive, then there is a catching-up. In fact, (7) implies full catching-up or complete convergence. To verify this, substitute (7) into (6), to see that all countries converge to the same adoption level (holding other variables constant) at time $t = 1/\lambda$. Gruber and Verboven (2000) imposed a full catching-up specification in their analysis of E.U. countries.

The present study also considers a partial catching-up specification, in which countries still converge at $t = 1/\lambda$, except for *a fraction σ of the difference in their initial adoption levels*. Let country i's initial adoption level, at the introduction date $t = T_i^0$, be $z_{iT_i^0} = \alpha_i^0 + \beta_i^0 T_i^0$. A generalization of (7) then is:

$$\beta_i^0 = \beta^0 - \lambda\left(\alpha_i^0 - \sigma\left(\alpha_i^0 + \beta_i^0 T_i^0\right)\right). \tag{8}$$

Substitute (8) into (6), to verify that countries converge at $t = 1/\lambda$, except for a fraction σ of the difference in the initial adoption level $\alpha_i^0 + \beta_i^0 T_i^0$. For example, if σ=0 (and λ>0), then convergence is complete as under (7); in contrast, if σ=1 (and λ>0), then countries converge except for the full difference in the initial adoption level. For any σ, (8) still implies that two countries with different introduction dates converge at $t = 1/\lambda$, provided they started at the same initial adoption level. Thus (8) allows us to focus on the speed of convergence between countries that have different introduction dates and are similar otherwise, while allowing for partial or no convergence between countries that start from different initial adoption levels. To clarify this, Figure 1 plots the (transformed) diffusion curve for three countries when (8) holds and σ=1. Country 1 and 2 start at a different introduction date but at the same level.

They fully converge at $t = 1/\lambda$. Country 1 and 3 have a different adoption date and also start at a different level. They converge at time $t = 1/\lambda$, up to the initially different level. Countries 2 and 3 start at the same date but at a different level; they do not converge.

The timing of additional entry licenses.

The effects of additional entry licenses are taken into account through several dummy variables D_{it}^{j}. We make a distinction between introducing competition among analogue operators, and introducing competition between digital operators. Furthermore, we distinguish between simultaneous entry, where two or more operators enter at once, and sequential entry, where one operator enjoys a monopoly period before additional entrants enter. Finally, we distinguish between an initial effect of competition on diffusion growth, and the effect after one year. The reasons for including all these variables have been discussed in the previous section. We now define the various dummy variables more precisely.

- COMP_A, COMP_D: dummy variables equal to 1 as soon as competition between analogue or digital operators is introduced
- SIMCOMP_A, SIMCOMP_D: dummy variables equal to 1 as soon as simultaneous competition between analogue or digital operators is introduced
- SEQCOMP_A, SEQCOMP_D: dummy variable equal to 1 as soon as sequential competition between analogue or digital operators is introduced.

For the sequential competition variables we also considered one-period lags. These lags measure the effect on the diffusion growth in the year prior to competition. They thus capture the possibility of pre-emption by incumbents. For both the sequential and the simultaneous competition variables we also considered one-period leads. These variables measure whether the effects of competition occurred mainly in the first year, or also persisted in later years.

Technological systems and competition between technological systems.

For each country we know the technological systems that are available: these include NMT, TACS, AMPS, C450 and national systems for the analogue technologies, and GSM and non-GSM systems for the digital technologies. We considered the effect of all these technologies separately. To simplify the exposition, we summarize the effects of the different technological systems through the following variable:

- DIGITAL: dummy variable equal to 1, if a digital system has been introduced.

We also introduce variables to measure the effect on the diffusion when different technological systems compete with each other:

- COMPSYST_A, COMPSYST_D: dummy variable equal to 1, if there are two or more competing analogue or digital systems. Since the variable DIGITAL is included, COMPSYST_D measures the additional effect of competing digital systems relative to the independent effect of the digital technology.

To capture the effects on the diffusion when a digital system is introduced without a previously introduced and co-existing analogue system, we introduce the following variable:

- SINGLE_D: dummy variable equal to 1, if a digital system is introduced without a previously introduced and co-existing analogue system.

Country characteristics.

We include the following country characteristics in x_{it}.

- GDPCAP: income per head, real gross domestic product per capita in U.S. dollars.
- MAINCAP: the number of fixed mainlines per capita. This variable captures the size of the fixed network, which may be a substitute or a complement for a mobile phone.
- WAITLIST: the waiting list for a fixed line connection, the ratio between registered applications for a fixed line and the number of connected fixed line subscribers. It captures the efficiency of the fixed operator, as well as the current "excess" telecom demand.

4.3. Data description

The study uses annual data for 140 countries that have adopted cellular telecommunications. Apart from the countries that have not adopted cellular telecommunications, 22 mostly very small countries are excluded. In total, the sample represents 94% of the world's population. The time series starts in 1981 and thus covers all cellular markets from the first year, with the exception of Japan where this was introduced in 1979. The data on the number of analogue and digital subscribers, the waiting list and the number of fixed mainlines is from the World Telecommunications Indicators of the ITU (1999). The information about the type of system is gathered from various sources, such as the trade press (*Mobile Communications* and EMC), GSM Memorandum of Understanding (http:\\www.gsmworld.com), Beckers and Smits (1997) and Garrard (1998). The macroeconomic data such as GDP and population are taken from the World Bank's World Development Indicators.

Tables 2 and 3 present some descriptive statistics on the diffusion levels at different point in time, and on the included explanatory variables.

5. Empirical Results

We estimated the diffusion model using nonlinear least squares. We could not reject restriction (5), which imposes a continuous change after a new event, for any specification. We thus concentrate on the restricted diffusion model (6). Table 4 presents the estimates for various alternative specifications.[11]

(insert table 4 about here)

The first column shows estimates when country characteristics are excluded and constraint (7) is applied, i.e. σ=0 (full international convergence at estimated time $t = 1/\lambda$). The second column shows estimates when country characteristics, GDPCAP, MAINCAP and WAITLIST are also included. The third column allows λ to vary across groups of countries. The fourth column generalizes (7) to the more flexible constraint (8).

The effect of country characteristics

Specifications (ii)-(iv) show that countries with a high income per capita (GDPCAP) tend to be more advanced in adopting mobile phones, yet the effect is diminishing over time. The overall effect of income on mobile penetration remains positive roughly until 2010 (for specification (ii)). This is intuitive, given the large fraction of the budget to be spent on a mobile phone during the early years, and the declining prices afterwards. Similarly, countries with a large fixed network (MAINCAP) tend to be more advanced in adopting mobile phones. Yet again the effect is diminishing over time and becomes negligible around 2007

[11] We considered the robustness of our empirical results in various respects: (i) impose (7) or its generalization (8), or estimate the fixed effects between α_i^0 and β_i^0 freely; (ii) include or exclude the country characteristics variables; (iii) restrict the market potential to the same proportion for all countries, or allow the proportion to vary across countries according to income class and urbanization level. The empirical results remained robust with respect to changes in any of these dimensions.

(for specification (ii)). This suggests that the fixed network is largely viewed as a complement to mobile phones. Finally, countries with a large waiting list for a fixed line connection initially have lower mobile penetration levels. Yet these countries experience a very strong and significantly higher annual growth rate than countries with a low waiting list. This brings them to more advanced adoption levels from 1987 onwards. Mobile telecommunications may thus be a very suitable tool for providing telecommunications access in inefficient fixed line markets, i.e. more typically developing countries.

The timing of first entry licenses

Let us now consider the relevance of the timing of first entry licenses, by looking at how fast early and late-coming countries converge. Columns (i) and (ii), which impose restriction (7), find a precise estimate of λ of .029 and .027, respectively. Countries that are less advanced in the level of adoption thus catch up by growing faster than early countries. Nevertheless the catching-up effect is very slow: the date of convergence in adoption levels ($t = 1/\lambda$) is t=34.5 and t=37.0, in the specifications under column (i) and (ii), respectively (with standard errors of 2.1 and 5.1 respectively. Because t=0 corresponds to the year 1980, this means that countries would converge in 2014 and 2019, respectively (with 95 percent confidence intervals of 2010-2018 and 2009-2029, respectively). The estimated convergence dates are later than in Gruber and Verboven (2000), who found convergence around 2008. This is not surprising given that the set of countries is now much more heterogeneous than the E.U. countries.

To incorporate the heterogeneity between countries, we relaxed restriction (7) in two ways. First, we allowed λ to vary across the following four groups of level of economic development (according to the World Bank classification): low, lower-middle, upper-middle and high-income countries.[12] The estimates in column (iii) show that there are indeed significant differences in catching-up across the four groups of countries. The least developed group 1 and group 2 countries show the slowest convergence (around year 2013), preceded by group 3 countries (around 2008) and group 4 (around 2006). Even though late-coming countries thus catch up faster if they come from more developed countries (group 3 and group 4), the delay is still substantial.

Second, we included the possibility of partial convergence, using (8) instead of (7). Convergence may now occur except for a fraction σ of the difference in initial adoption levels. This allows us to focus on convergence between countries with different introduction dates that are similar otherwise. (see section 4.2). The results in column (iv) now show an estimate of λ equal to 0.046 and an estimate of σ equal to .78. According to this specification countries converge around 2002, except for 78 percent of the possible difference in the initial adoption level. Referring to Figure 1, this means that two countries issuing a first license at a different point in time but with the same intial level converge around 2002, whereas countries with different initial adoption levels show little convergence. Intuitively, the effects of regulatory delay in issuing first licenses persist until 2002.[13] Any remaining lack of convergence after that time follows from persisting initial differences in adoption levels across countries.

The introduction and timing of additional entry licenses

All specifications in Table 4 consider the effects of introducing two or more competing operators during the analogue and during the digital era. One can see that introducing

[12] Instead of assuming that different groups of countries converge at different dates, it would be interesting to let the data speak on grouping countries that seem to converge.

competition between operators had a significant impact on the growth of mobile diffusion. The effect was especially large during the digital era, and less pronounced during the analogue era. This is consistent with our hypothesis in section 3 that capacity plays a major role in explaining the magnitude of the competition effects. During the analogue era capacity was constrained, thereby mitigating the positive effects from competition. Casual evidence suggests that prices indeed remained relatively high after the introduction of competition during the analogue era.

The discussion in section 3 suggested that in addition to capacity also consumer switching costs may influence the effects from competition. To investigate this, Table 5 extends specification (i) of Table 4, to explore the competition effects in further detail, comparing simultaneous with sequential entry, and distinguishing between pre-emptive, immediate and future competition effects. The first column compares the effects of simultaneous and sequential entry (SIMCOMP_A versus SEQCOMP_A, and SIMCOMP_D versus SEQCOMP_D). It can be seen that the impact on the diffusion of mobile adoption was substantially stronger when entry was introduced sequentially than when it was introduced simultaneously. The sequential entry effect is especially strong during the digital era when capacity is larger, but it is also present during the more capacity constrained analogue era. One explanation for the stronger sequential entry effect is that the mobile market is still growing: since competition is on average introduced at a later date under sequential entry, some catching up may be expected. An alternative explanation is that a new sequential entrant needs to price rather aggressively to obtain at least some market share if the incumbent's consumers face significant switching costs.

(insert table 5 about here)

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[13] Some studies indicate high welfare costs from regulatory delays in issuing licences, e.g. Hausman's (1997)

To further explore the role of switching costs, we considered pre-emptive, immediate and future competition effects. The second column of Table 5 distinguishes between the competition effect during the first full year of competition and the effect afterwards, by introducing a lead variable of the competition variable. Quite interestingly, it can be seen that most of the competition effect takes place during the first year. For simultaneous entry during the analogue and the digital eras, the competition effects are 0.793 and 0.271 during the first year of competition, and drop to insignificant numbers of 0.793-0.855=-0.062 and 0.271-0.222=0.049 afterwards. For sequential entry during the analogue period, the competition effect is 0.713 during the first year of competition, and drops to an insignificant number of 0.713-0.703=0.010 afterwards. Only for sequential entry during the digital era the competition effect remains large after the first year (0.631-0.026=0.605). Yet this is because for this particular case our sample has few years of observations after the second entrant has entered.

The fact that competition mainly influences the diffusion during the first year is consistent with our hypothesis that consumers have switching costs, as discussed in section 3. During the first year, firms compete vigorously to build up market share to exploit market power in the future stages. Once an installed base is built up, competition becomes softer. Note that competition does not become so soft to actually lower the adoption level or to reduce the adoption growth below the pre-competition rate. This is because in this market there appear new consumers to compete for in every period.

The third and fourth columns of Table 5 investigate whether, in the case of sequential entry, incumbents have an incentive to pre-empt in the period prior to actual entry. This may be done, for example, through limit pricing (charging lower prices than a monopolist) or by

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estimate that regulatory delay in analogue cellular licenses has costed the US economy 100 billion US$.

following aggressive marketing campaigns[14]. While switching costs may explain incumbent's limit pricing as a strategy to build up a market share to exploit future market power, it is not the only possibility. In fact, an incumbent may "limit overprice" (charge higher prices than a monopolist), if it is more important to induce soft competition by the future entrant. Limit pricing is more likely if switching costs are present but not too large, and if there is a significant growth of new consumers.

To assess the presence of pre-emptive behavior, we included a lagged dummy variable for the sequential entry variables. The third column shows that this lagged variable has a significant and large effect during both the analogue and the digital eras. This suggests the presence of pre-emptive behavior by incumbent firms, through limit pricing, aggressive marketing campaigns or otherwise. To obtain further insights, the fourth column constrains the effect of the lagged (pre-emption) competition variable to be the same as the actual competition variable. This shows more precisely how the diffusion level in the analogue era is increased especially during the year preceding competition and the year of actual competition.[15]

To summarize this analysis, we find that competition has a stronger impact during the digital era than during the analogue era, thanks to the drastically increased capacity. We also find that competition especially induces diffusion during the early years (or even in the preceding year in the case of sequential entry), and that sequential entry has a stronger impact than simultaneous entry. This is consistent with the presence of consumer switching costs, accounting for the fact that there also appear new consumers every period.

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[14] A example in this respect is the UK. In spite of a duopoly during the second half of the 1980s and the early years of 1990, prices for mobile telecommunications stayed constant in nominal terms. Only the sequential entry of two further firms in 1993 and 1994 respectively induced a pattern of falling prices (Valletti and Cave, 1998).

[15] The fact that for analogue sequential entry the competition effects are lower in specification (iii) and (iv) as compared to specification (ii) does not mean that the results are not robust. This is because (ii) does not take into

The role of technological systems and systems competition

Tables 4 and 5 also include an assessment of the effects of different technological systems. First, note that the presence of a digital technology (DIGITAL) has only a modest independent impact on the diffusion growth. Quite intuitively, the beneficial capacity impact of the digital technology works best in those cases where it has been combined with the introduction of competition (COMP_D), as discussed before. Similarly, the introduction of the digital technology without a preceding analogue period (SINGLE_D) had no significant independent impact. This suggests the absence of a lock-in effect into the less efficient analogue system.

Now consider the effects on the diffusion growth when there were two or more competing analogue or digital systems, measured by COMPSYST_A COMPSYST_D. Table 4 suggests that competition between analogue systems (e.g. NMT and TACS) slowed down the growth in mobile diffusion. This is confirmed by large and significant negative annual growth effects of about 6-7 percent in the more elaborate specifications of Table 5.[16] Competition between digital systems (GSM and non-GSM) also seemed to slow down diffusion. While the negative point estimates for the effect of digital systems competition seem quite substantial, they are also rather imprecise. This is because there are only few observed cases.

To interpret this, recall that there may be both advantages and disadvantages from having competing systems rather than single standards. The major advantage of allowing competing systems is that markets may not be locked in into inferior technologies and that firms are motivated to continuously invest in R&D to improve the quality of their technology. Major disadvantages of allowing competing systems are that network externalities are more limited

account pre-emptive effects. To properly compare (ii) with (iii) and (iv), one should add the pre-emptive and actual effects in specifications (iii) and (iv). One then obtains a similar cumulative effect.

(especially when roaming is valued highly) and that economies of scale in the manufacturing of equipment are not fully exploited. Our empirical results thus indicate that the disadvantages of competing systems (network effects and scale economies) were dominant during the analogue era. During the digital era, the disadvantages may have been partly balanced by the advantages from technological systems competition. This is consistent with the view by Shapiro and Varian (1999), who argue that the decentralized systems competition approach followed in the U.S. may have hindered diffusion of the current technology, but gave the innovative CDMA technology a chance to develop: CDMA is now the basis for the so-called "third generation" mobile telecommunications such as UMTS.

6. Conclusions

This paper has looked at the effects of entry regulation and standard setting on the evolution of the cellular mobile telecommunications services industry, controlling also for a set of country specific variables. It is shown that policy design of market structure has to take account of the technological constraints. One can distinguish between an analogue phase, during which the industry was potentially capacity constrained, and a digital phase, during which these constraints were relaxed. Government policies affected the evolution of the industry in a different way during both phases.

First, the actual timing at which first entry licenses are issued had a significant impact on the diffusion of mobile services. The effects of regulatory delay in issuing first licenses on cross-country differences in adoption levels are felt until around 2002. After that time, a lack of convergence has to be attributed to persisting initial differences in adoption levels.

[16] Even stronger and significant negative effects (between –5 and –14 percent) were obtained in specifications that distinguished between the different quality effects of the NMT, TACS, AMPS and C450 analogue technologies. To simplify the exposition, we do not report the results of these specifications.

Second, the introduction of second entry licenses (competition) had a significant impact on the diffusion of mobile services. The effect is especially strong during the digital phase. This is consistent with the existence of binding capacity constraints during the analogue phase, compared to a drastically expanded capacity in the digital phase. This confirms the expectation that competition speeds up diffusion.

Third, the timing at which second licenses are introduced turns out to be very relevant. Simultaneous entry has a modest (but significant) impact on the diffusion, whereas sequential entry has a stronger impact, especially during the digital phase. Most of the competition effect takes place during the first year of competition. In the case of sequential entry, the competition effect also takes place in the year prior to second entry, indicating pre-emptive behavior by the incumbent. These findings can be explained by strategic behavior by the operators in the presence of consumer switching costs.

Finally, setting technology standards rather than allowing multiple competing systems is a relevant determinant of the evolution of the industry. We find that a single analogue standard helps to develop the market significantly faster compared to competing analogue systems. This is consistent with the presence of network effects and scale economies. Imposing a single digital standard (e.g. the GSM in the E.U.) also seems to stimulate diffusion, yet the effect is imprecisely estimated; a longer time horizon is required to assess whether the advantages from systems competition in the digital era (e.g. the emergence of the new CDMA system to be used for third generation mobile telecommunications) are outweighed by the network and scale advantages from a single standard.

With respect to country characteristics we find that income per capita and the size of the fixed network have a positive (but declining effect) on the level of diffusion. The length of the waiting list for the fixed network also has a positive effect on the level of diffusion, suggesting that mobile telecommunications is a suitable alternative in providing telecommunication access inefficient fixed line markets. One of the broader policy conclusions that can be drawn from this paper is that public policy decisions typically have a persistent effect on the evolution of regulated industries. Therefore the cost of regulatory failure can be very high. Firm entry and their timing are important determinants for market evolution and this importance increases as capacity constraints are relaxed. More research is necessary to better understand the determinants of firm behavior in such industries, by for instance using market share data. Robust results are becoming increasingly important for providing policy advice; there will be mounting requests for regulating market structure in emerging network segments of the information and communications industry, which by their nature tend to be concentrated.

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Tables and figures

Table 1. The policy matrix: number of countries adopting different policies for analogue/digital cellular systems (Status 1997).

	Single system (Standard)	Multiple systems	Total
Monopoly	83/39	5/0	88/39
Oligopoly	22/40	8/8	30/48
Total	105/79	13/8	108/87

Note: First/second number refers to the countries adopting analogue/digital cellular systems.
Source: World Telecommunications Indicators, Mobile Communications and EMC; own calculations.

Table 2. Descriptive statistics – Included variables (1050 observations)

	Average	St. Dev.	Min.	Max.
DIGITAL	0,284	0,451	0	1
SINGLE_D	0,066	0,248	0	1
COMPSYST_A	0,089	0,284	0	1
SIMCOMP_A	0,061	0,239	0	1
SEQCOMP_A	0,114	0,318	0	1
COMPSYST_D	0,014	0,119	0	1
SIMCOMP_D	0,120	0,325	0	1
SEQCOMP_D	0,026	0,158	0	1
GDPCAP	11136	11533	141	47840
MAINCAP	7148182	19411600	4215	172452000
WAITLIST	286027	975325	0	10998700

Table 3. Descriptive statistics – Mobile penetration rates (in percent)

	Number of cases	Average	St. Dev.	Min.	Max.
	After first full year of introduction				
All countries	139	0,3	0,6	0,0	6,5
LDC	75	0,1	0,3	0,0	1,8
MDC	64	0,4	0,9	0,0	6,5
	After fifth full year of introduction				
All countries	91	1,7	2,3	0,0	12,6
LDC	31	0,9	1,7	0,0	8,2
MDC	60	2,1	2,5	0,1	12,6
	After tenth full year of introduction				
All countries	36	6,2	5,5	0,0	26,4
LDC	6	0,7	1,1	0,0	2,8
MDC	30	7,3	5,4	0,4	26,4
	At the end of 1985				
All countries	140	0,0	0,2	0,0	1,5
LDC	76	0,0	0,0	0,0	0,0
MDC	64	0,1	0,3	0,0	1,5
	At the end of 1990				
All countries	140	0,4	0,9	0,0	5,4
LDC	76	0,0	0,2	0,0	1,8
MDC	64	0,8	1,2	0,0	5,4
	At the end of 1995				
All countries	140	2,6	4,5	0,0	22,7
LDC	76	0,4	1,4	0,0	10,0
MDC	64	5,2	5,4	0,1	22,7

Note: LDC: Less developed countries (income class 1 and 2 according to World Bank Classification). MDC: More developed countries (income class 3 and 4 according to World Bank Classification).

Table 4. Empirical results for diffusion equation (6)

	(i)		(ii)		(iv)		(iv)	
λ	.029**	(.001)	.027**	(.002)	.030**	(.002)	.046**	(.002)
λ_2					.000	(.002)		
λ_3					.006**	(.001)		
λ_4					.009**	(.002)		
σ							.776**	(.074)
β_0	.176**	(.017)	.194**	(.033)	.110**	(.026)	.233**	(.030)
Growth parameters for competition variables								
COMP_A	.059**	(.017)	.039*	(.020)	.032*	(.017)	.037*	(.021)
COMP_D	.155**	(.041)	.134**	(.045)	.119**	(.043)	.181**	(.045)
Growth parameters for technology variables								
DIGITAL	.059	(.039)	.067*	(.044)	.086*	(.043)	-.005	(.044)
SINGLE_D	.055	(.078)	.061	(.085)	.013	(.078)	-.110	(.092)
COMPSYST_A	-.036	(.024)	-.044*	(.026)	-.046*	(.023)	.002	(.027)
COMPSYST_D	-.198	(.151)	-.131	(.189)	-.009	(.184)	-.182	(.184)
Location parameters for country characteristics								
GDPCAP			.143**	(.027)	.142**	(.031)	.101**	(.022)
MAINCAP			.747**	(.260)	1.091**	(.347)	.925**	(.197)
WAITLIST			-.237	(.222)	-.090	(.236)	-.413*	(.198)
Growth parameters for country characteristics								
GDPCAP			-.005**	(.001)	-.007**	(.002)	-.001	(.001)
MAINCAP			-.029**	(.012)	-.053**	(.018)	-.026**	(.008)
WAITLIST			.052**	(.013)	.048**	(.014)	.066**	(.014)

* Statistically significant at 5 percent level.

** Statistically significant at 1 percent level.

Standard errors in parentheses.

Table 5. Simultaneous versus sequential entry effects, and technological systems competition

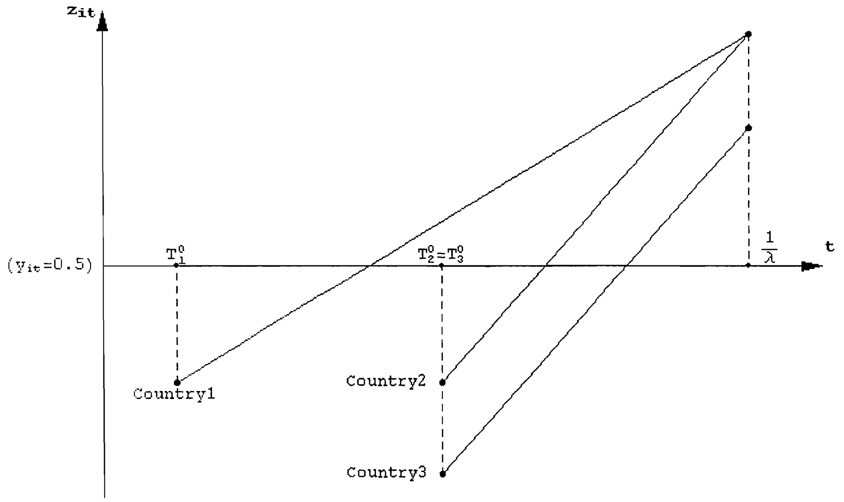
	(i)		(ii)		(iii)		(iv)	
				Analogue technology				
SIMCOMP_A	.018	(.023)	.793**	(.267)	.800**	(.266)	.800**	(.266)
SIMCOMP_A(+1)			-.855**	(.293)	-.860**	(.292)	-.859**	(.292)
SEQCOMP_A(-1)					.297*	(.166)	.394**	(.065)
SEQCOMP_A	.112**	(.023)	.713**	(.122)	.197	(.309)		
SEQCOMP_A(+1)			-.703**	(.141)	-.479**	(.183)	-.377**	(.084)
COMPSYST_A	-.073**	(.025)	-.060**	(.025)	-.065**	(.026)	-.065**	(.025)
				Digital technology				
SIMCOMP_D	.141**	(.041)	.271**	(.066)	.299**	(.067)	.298**	(.066)
SIMCOMP_D(+1)			-.222*	(.106)	-.231*	(.105)	-.231*	(.105)
SEQCOMP_D(-1)					.447**	(.188)	.411**	(.098)
SEQCOMP_D	.465**	(.096)	.631**	(.185)	-.082	(.353)		
SEQCOMP_D(+1)			-.026	(.024)	-.008	(.025)	-.013	(.018)
COMPSYST_D	-.129	(.151)	-.083	(.149)	-.088	(.148)	-.091	(.148)

* Statistically significant at 5 percent level.

** Statistically significant at 1 percent level.

Standard errors in parentheses.

Figure 1.



Note: Figure 1 shows the diffusion for three countries under equation (8), assuming σ=1. Country 1 and 2 start at a different introduction date, but at the same diffusion level. They fully converge at t=1/λ. Country 1 and 3 start at a different adoption date and also at a different diffusion level. They converge at t=1/λ, except for the full amount of the initially different level (since σ=1). Country 2 and 3 start at the same date but at a different level. They do not converge (since σ=1). To depict situations where σ<1, the curve for country 3 needs to be modified: the endpoint increases until it reaches the endpoint of the other two countries for σ=0.