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Entry, standards and competition : firm strategies and the diffusion of mobile telephony

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Entry, standards and competition: firm strategies and the diffusion of mobile telephony

Heli Koski[*] and Tobias Kretschmer[**]

Abstract

This paper studies the effects of a country's regulatory setting and competitive environment on the performance of second-generation (2G) mobile telecommunication. We consider three dimensions of sector performance: entry time, service prices and diffusion. We address the question of non-random selection arising from cross-country differences in the timing of the commercialization of new technologies. Our empirical exploration shows that this type of sample selection may indeed be a substantial problem in cross-country studies on technology diffusion and yield biased estimates of the policy variables of interest.

Our estimation results suggest that standardization accelerates 2G entry and diffusion, although within-standards competition triggers less aggressive price competition than between-standards competition. We also find that an early monopolist will price more aggressively to build up an installed base. Furthermore, we find that liberalizing markets for incumbent technologies (i.e. fixed line telephony) has accelerated the commercialization of 2G.

Keywords: competition, standardization, diffusion, pricing, mobile telephony

JEL Codes: L1, L52, O38

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1. Introduction

Telecoms regulators faced two crucial decisions in the context of introducing second generation (digital) mobile telecommunication (2G): whether to allow competition *between technologies* and/or *within technologies*. The first decision corresponds to selecting a *technology standard*, the second is about issuing licenses to *multiple operators*. Our paper studies the effect of both these decisions on the evolution of the 2G mobile industry along three dimensions: entry timing, service prices, and diffusion speed. That is, we ask the following questions: i) How are entry, prices and diffusion affected by the regulator's choice of technological standardization and competition? ii) Are the three dimensions of industry evolution interlinked, i.e. is it important to control for the interaction among them?

Our empirical results suggest that standardization significantly accelerates 2G entry and diffusion, although standardization triggers less aggressive price competition than competition between standards. We also find that an early monopolist will price more aggressively to build up an installed base and that liberalizing markets for incumbent technologies (i.e. fixed line telephony) has accelerated the commercialization of 2G. Finally, we find that controlling for the linkages between the three dimensions significantly improves our results, suggesting that the studies of the evolution of a market have to consider all three dimensions jointly.

The contribution of our paper is twofold. First, we illustrate that the effects of standardization and competition on the 2G market were not as clear-cut as commonly assumed. In particular, we find that competition has little or no direct effect on the diffusion of the technology once we are controlling for mobile service prices. Put differently, other policy instruments lowering prices (e.g. encouraging cost-saving investments, ensuring number portability etc.) may be equally effective in accelerating diffusion while avoiding having to duplicate fixed network investment cost. Standardization on the other hand has two apparently countervailing effects: firms competing in a standardized market compete less fiercely, presumably because the consequences of falling behind in such a competition are not as consequential. On the other hand, after controlling for price as an endogenous variable, standardization appears as a statistically significant facilitator of diffusion.

Second, our paper makes a methodological point. We propose that cross-country differences in the timing of commercialization of technology may cause biased estimates of the explanatory variables of the technology diffusion equation. This happens as we observe diffusion data only among countries for which commercialization or market entry has become profitable. Thus the error terms of the selection equation of market entry and performance equation may be correlated and cause a classic sample selection bias (see Heckman, 1979). Our data indicate that the sample selection bias may indeed be substantial and to isolate the "true" effects of regulatory variables we need to control for this bias.

Our paper is part of a growing empirical literature on telecommunications markets. Previous contributions were either multiple-country, single-equation models (Gruber and Verboven, 2000, 2001, Jang et al., forthcoming) or single-country, multiple-equations models (Grajek, 2003, Doganoglu and Grzybowski, 2004). Neither of these models however incorporate the determinants of entry in their estimations. Dekimpe et al. (2000) develop an interesting approach which links the entry and diffusion processes, but their measure of diffusion (a predefined cutoff level of penetration in the market) is rather crude and they do not incorporate competition effects in their model. Our model is closest in spirit to Gruber and Verboven (2001, GV 2001 thereafter) since they also explicitly include the effect of competition in the speed of mobile diffusion in a panel of countries. However, their dataset does not include service prices, and thus they cannot assess the effect of policy instruments on diffusion and prices separately.

The rest of the paper is organized as follows. Section 2 discusses the evolution of the 2G mobile markets in our sample countries. A discussion on the economics of entry, diffusion and pricing follows in Section 3. We introduce our data and define the variables used in Section 4, and report our estimation results in Section 5. Section 6 concludes the paper with policy implications and suggestions for future research.

2. The market for digital mobile (2G) telephones

The diffusion of 2G began in January 1992, when the first wireless digital telecommunications network started operating in Finland. The first year of digital service provision varied greatly in our sample, despite the fact that technologies were internationally available and transferable (see Figure 1).

[Insert Figure 1 here]

The first generation of mobile telephones never reached high levels of penetration for several reasons, including technological uncertainty,[1] inefficiency in spectrum use and a lack of competition. Digital mobile telephony meant a drastic increase in the efficiency of spectrum use and in service quality: digitalization facilitated the introduction of new services (e.g. Short Messaging Service or SMS) and increased consumer privacy. Simultaneously, regulators allocated more frequency spectrum for mobile communication services.

[1] At that time, eight analogue mobile telephony standards were active in different parts of the world, with none of them able to command a sufficiently high subscriber share to tip the global market.

[Insert Figure 2 here]

The latter part of Figure 2 shows that 2G diffusion was still increasing and global penetration still relatively low in 1999. Plotting maximum, minimum and average diffusion rates in our sample countries however, we find that diffusion rates differ dramatically (Figure 3). This divergence in early diffusion rates across relatively similar countries[2] presents something of a puzzle and is the focus of our paper.

[Insert Figure 3 here]

Apart from the differences in entry times documented in Figure 1, demographically similar countries differ in the competitive parameters set in the market, which may have been the cause for variations in diffusion speed. We discuss two of the most important parameters of market design, namely the number of 2G operating licenses and the setting of a technological standard in the following section.

3. Economics of entry, diffusion and pricing – standards and competition

(i) Standards and competition

Typically, more than one 2G license was issued per country. Operators that have been issued a license, however, did not automatically start servicing straightaway, so that competition developed only gradually in the mobile market.[3] Previous empirical studies find a clear positive relationship between competition and mobile diffusion (Barros and Cadima 2000; GV 2001) and stress the importance of promoting competition for market performance. In both studies, the (unmodelled) mechanism by which competition accelerates diffusion is assumed to be price.

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[2] All countries in our sample are classed either as high- or upper-middle incomes countries by the OECD.

[3] In 1992, only about one fourth of the sampled countries had more than one digital wireless service provider, whereas in 2000, about 97% of the markets were oligopolies.

Another important regulatory decision that was informed by technological considerations was the degree of technological standardization. That is, even where multiple licenses were issued, some national regulators required all license holders to operate in the same technological regime (e.g. GSM in European Union countries). Other countries such as the United States have left the choice of 2G standard open, letting the market decide upon the degree of standardization. As a consequence, four groups of digital mobile telephony systems – GSM, CDMA, TDMA and PDC – were introduced in different parts of the world.

The question of whether an ex-ante (*de jure*) standard or an ex-post (*de facto*) standard generates superior results remains open. *De jure* standard setting has the advantage of avoiding uncertainty and confusion among consumers (Kretschmer 2004), which may help a new technology get adopted. *De facto* standardization on the other hand allows technologies to continue developing and to let the market select possibly a better technology at a later stage. It is difficult to weigh up the expected losses from choosing an inferior technology too early (*de jure*) against the interim losses from having two incompatible user groups for some time (*de facto*), and outcomes have often been shown to depend crucially on the modelling assumptions.[4]

(ii) Entry, pricing and diffusion

Who makes the decision to launch a new telecommunications technology? When studying the entry process, it is crucial to identify the relevant actors and their objectives. Historically, most national telecommunications markets have developed from a state-owned regulated monopoly to limited competition in some submarkets

[4] See Koski and Kretschmer (2004) for a discussion of the main theoretical results in the literature and their qualifications in empirical work.

(often international telephony), to full competition.[5] In most of the countries we study the incumbent monopolists were still the strongest market players at the time of the emergence of mobile telecommunications (OECD 1999). Most countries were at an intermediate stage of liberalization at the time of 2G introduction, which is why we need to make some assumptions about the nature of the decisionmaking process.[6] In particular, we note that information about 2G prior to its introduction was limited, and operators of existing telecommunications services were most likely to possess this information,[7] which gave incumbents an opportunity to orchestrate or at least influence the date at which 2G should start operating.[8] Our assumption (which is reinforced by the observation that incumbent operators usually had a seat on the board of national regulators) therefore is that the decision to launch 2G is made in line with the interests of incumbents from the fixed-line and 1G markets.[9]

The entry of 2G is therefore likely to be influenced by the respective profits gained from the existing technologies as well as the expected profits from the new technology. In other words, the timing of first entry is assumed to be a function of current and expected future profits:

$$\tau_E \equiv t_E - t_0 = \tau_E\left(\Pi_F, \Pi_1, E(\Pi_2)\right), \tag{1}$$

[5] The US is a notable exception to that pattern in that telephony had been liberalized at a much earlier stage of the industry.

[6] It would be easy to identify the decisionmakers in the two extreme cases: Under a fully regulated monopoly, the state would be able to optimally choose the introduction time of a new generation, while in a fully liberalized market firms themselves would be deciding when to enter a new market.

[7] According to a Telenor executive, the Norwegian Telecommunications Authority NPT relied strongly on Telenor, the incumbent operator, and handset producers like Nokia and Eriksson for information on the technological state of digital mobile telephony prior to its introduction.

[8] We observe a similar pattern in the ongoing negotiations on network number portability. Despite being technologically feasible for years, many countries are only introducing it now as a consequence of the long list of concerns brought forward by strong incumbents, who have most to lose from a decrease in switching costs for existing customers.

[9] Prieger (2001) develops a model in which a regulated firm strategically reveals information to the regulator by announcing technological innovations. He finds that by signalling to the regulator (who in turn selects a length of time to approve the product), the firm can hasten or delay the introduction of a product into a market to its advantage.

where τ_E is the time difference between global availability of 2G technology and introduction and Π_i are net (flow) profits of fixed-line (F), first-generation mobile (1), and second-generation mobile (2) telephony, and E(·) is the expectations operator. Entry timing could be studied either by using a spells specification with the length of a spell (τ_E in eq. (1)) as the dependent variable, or analogously with a hazard rate model that estimates the probability $\lambda(t)$ of a spell ending between t and $t+\delta$.[10] We choose the second approach and can therefore write the hazard rate of country i in year t, given that it has not introduced 2G yet, as

$$h_i(t) = h_0(t) \cdot \lambda_{it}, \qquad (2)$$

where $\lambda_{it} = \exp(x_{1it}\beta_1 + \varepsilon_{it})$ is a vector of covariates proxying for Π_F, Π_1, and $E(\Pi_2)$, and $h_0(t) = \gamma\, t^{\gamma-1}$ is the baseline hazard in a Weibull specification. Note that variables that decrease τ_E will increase $h_i(t)$, the hazard rate.

We can make the following assumptions about the profit functions: first, the more profitable 2G is expected to be, the earlier entry will occur, which represents the rank effect in diffusion theory (Karshenas and Stoneman 1993). Second, we assume that fixed-line telephony and 2G mobile are substitutes. (Barros and Cadima 2000, Liikanen et al. forthcoming). Third, we assume that 1G profits are an indicator for expected 2G profits. In the case of a new technology, early generations often shape consumer preferences, and firms are able to estimate demand more precisely. In the case of 1G, capacity was also limited, so that high 1G revenues (and therefore profits) indicate that capacity is likely to run out soon, thus triggering investment in a higher-capacity network.

[10] Integrating the hazard function over all time periods t' < t will generate the survivor function, i.e. the probability that a spell will last at least until t.

The effects of standardization and competition on the entry of new technologies have been discussed in the theoretical literature: Regibeau and Rockett (1996) show that with compatibility (i.e. standardization), first entry may be accelerated in order to delay future technology introductions. Conversely, Kristiansen (1998) shows that standardization may delay entry because there is no incentive to preempt another (incompatible) technology and build up an installed base. Finally, standardization reduces the uncertainty of future payoffs and therefore decreases a potential entrant's option value of delaying investment (Pindyck, 1991). Hence we would expect standardization (variable *STAND*) to accelerate entry due to the delay effect on future generations and the option value effect, but this effect will be mitigated by firms' decreased incentive to preempt each other in the compatible case.

Competition in previous-generation technologies (variable *COMPF*) is expected to accelerate entry via the first term in equation (1): lower current profitability increases incentives to introduce a new technology if the assumption of substitutability holds.

Previous studies on the diffusion of mobile phones have neglected the role of prices and entry in market dynamics. The goal of our study is therefore to take advantage of cross-country variations in inter- and intra-standards competition and discuss their effect on 2G pricing and diffusion separately.

A tractable empirical analysis of the aggregate diffusion of a technology among both firms and consumers demands a simplified analytical approach omitting strategic behaviour and individual preferences. We use the commonly applied *epidemic* model assuming that information spreads in an epidemic manner, i.e. over time more people will learn about a new technology and adopt it. We make a common assumption concerning the diffusion of mobile phones (see, e.g., GV 2001, Jang et al., forthcoming) that the fraction of the mobile phones adopted of the potential total number of mobile phones adopted in country i at time t follows a logistic growth curve:

$$N_{it} = \frac{N^*}{1+\exp(-\beta_0 - \beta_1 t)}, \qquad (3)$$

where N_{it} is the number of 2G mobile phones in country i at time t, N^* equals the network size of technology when its diffusion is complete[11], and β_1 captures the epidemic effect. A transformation of equation (3) produces the following model:

$$\log\left(\frac{\hat{N}_{it}}{1-\hat{N}_{it}}\right) = \beta_0 + \beta_1 t, \qquad (4)$$

where $\hat{N}_{it} = N_{it} / N^*$. Furthermore, our empirical exploration assumes that there is a vector of explanatory variables, X_{2it}, that may potentially affect the diffusion speed of mobile phone use.

Using only observed data on diffusion assumes that the diffusion speed of digital mobile phones is independent of the decision to launch 2G wireless services. We suggest that profitability (and therefore commercialization) of 2G wireless services has varied across countries (see discussion above), causing non-random selection of the sample used in our estimation of diffusion equation. To correct for this potential sample selection bias that may cause biased estimates of our explanatory policy variables of interest, we allow for correlation between the error terms of the equations for diffusion speed and the selection equation that defines whether the first mobile service operator has begun to offer wireless telephone services. We estimate the

[11] We bound the upper limits of the diffusion of the fixed and cellular telecommunications networks to be 100% for main lines and cellular phones, i.e. one main line and one cellular telephone per inhabitant. We reestimated our model using upper bounds of 80% and 120%, respectively, and found our results to be qualitatively robust.

diffusion equation on condition that market entry has happened (using the results from the estimation of the probit model for entry[12]) as follows:

$$\log(\frac{\hat{N}_{it}}{1-\hat{N}_{it}})\Big|N_{it} > 0 = \beta_0 + \beta^{'}(t + X_{2it}) + \rho_1 \sigma f(\gamma' Z)/F(\gamma' Z) + \varepsilon_{it} \,, \tag{5}$$

where $F(\cdot)$ and $f(\cdot)$ are the cumulative distribution function and density function of the standard normal distribution, respectively, σ^2 is the variance of the diffusion equation and ρ_1 is the correlation between the error terms of the entry and diffusion equations (see also Greene, 2003, pp.784-785). The last term of the equation – the inverse Mills ratio from the probit model – corrects for (potential) sample selection bias.[13] To the best of our knowledge, previous empirical studies on diffusion have ignored this sample selection bias.

Prices for mobile services are determined by the demand for services and the competitive environment of the firm. As costs of service provision may depend on technology choice and entry timing, we assume that the price equation may not be independent of the entry equation either. Consequently, we estimate the prices, as diffusion, conditional on entry having occurred and as a function of the Mills ratio obtained from the entry equation:

$$\log(P_{it})\Big|N_{it} > 0 = c_0 + c^{'}(t + X_{3it}) + \rho_2 \sigma f(\gamma' Z)/F(\gamma' Z) + \nu_{it} \,, \tag{6}$$

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[12] We first estimated the random effects probit model using LIMDEP 7.0 software (see LIMDEP 7.0 Manual, pp. 435, for the description of the model and estimation method) to investigate whether the error terms of the probit equation are autocorrelated and consequently, the estimation results of the pooled probit model inconsistent. Our findings – no autocorrelation – suggest that it is sufficient to use the simple pooled probit approach to calculate values for the inverse Mills ratio (for the basic probit model, see LIMDEP 7.0 manual, pp. 418-419). We basically follow the steps of Heckman's two-stage sample selection method (1979).

[13] A method that would explicitly investigate the impact of the timing of entry on diffusion and prices – for example, the inclusion of a per-country estimate of a country's "expected entry time" derived from the entry model – resulted in unstable estimation results due to the strong correlation with other explanatory variables.

where X_{3it} is a vector of explanatory variables and ρ_2 is the correlation between the error terms of entry and price equation. The estimation of ρ_1 and ρ_2 and the statistical significance of their estimates allows us to assess whether the Mills ratio variable controlling for sample selection bias is relevant in the performance equations.

We suggest that competition and standardization policy may be central factors contributing to differences in both pricing and diffusion speed of mobile telephony among industrialized countries. This view is consistent with previous theoretical and empirical studies on technology adoption in network markets. De-jure standardization (variable *STAND*) is expected to lead to faster diffusion of mobile telephony as expected network benefits are higher under compatibility and thus, as predicted by Katz and Shapiro (1985), result in higher output than equilibria with less than complete compatibility. There is some empirical support to this theory: Koski (1999) finds that standardization led to faster diffusion in the PC market, and Dranove and Gandal (2003) show that in the Digital Video market diffusion takes place at a slower rate if an incompatible technology had been preannounced.

Previous theoretical work does not provide clear guidance on how standardization influences service prices. On the one hand, when various incompatible technologies compete for market share and the industry standard, price competition intensifies since firms try to gain an installed base of users with high switching cost.[14] On the other hand, standardization is often said to generate economies of scale in production and service provision, leading to lower prices than in markets with incompatible technologies.

[14] For an extensive overview of competition with switching costs and network effects, see Farrell and Klemperer (forthcoming).

Competition in wireless telephony is expected to influence demand via prices – competition generally results in lower prices[15] – but it may also affect diffusion speed independently. Market presence by multiple firms may lead to higher product awareness, and non-price competition is likely to intensify, increasing adoption incentives beyond the pure price effect. 2G competition (variable *COMP*) is therefore expected to be positively related to diffusion and negatively related to 2G service prices.

The relationship between the degree of competition and mobile phone diffusion and service pricing may not, however, be so straightforward. In 2G markets, switching costs are substantial, arising for example through a lack of number portability,[16] SIM-locking,[17] and contractual obligations.[18] Therefore, especially in the early stages, firms have an incentive to secure a large number of locked-in consumers. This would imply a negative effect of immediate competition from the inception of the market (variable *MULTIE*) on service prices, and consequently a positive effect on diffusion that may be reinforced through non-price competition or introductory offerings of handsets to new subscribers. On the other hand, monopolistic markets may lead to faster technology diffusion as an early monopolist anticipates future entry and tries to build up an installed base prior to competition (GV 2001 find some evidence of such preemptive behaviour). One way to do this is to use monopoly penetration pricing (i.e. set prices even lower than marginal costs). Then, wireless telephony markets

[15] Parker and Röller (1997) and Nattermann (1999) confirm this for mobile telephony.
[16] During our sample period, wireless number portability was not an option in most countries. In other words, the decision to switch to use another wireless service provider inevitably meant a new mobile telephone number.
[17]SIM stands for Subscriber Identity Module. A SIM-card contains a microchip storing data that identifies the caller to the network service provide Since handsets were often sold at a discount, some providers modified them so that they would only operate with a specific provider's SIM cards – a practice called "SIM-locking".
[18] Most contracts had a minimum service period with a monthly rental fee that would have to be paid if the contract were terminated early.

controlled by a monopoly in the beginning might witness lower prices and higher diffusion than competitive markets.

4. Data

We use a panel of 32 industrialized countries over the years 1991 to 2000 (see Figure 1 for the list of countries). In the joint estimation of our price and diffusion model and the estimation of entry, our sample is limited to 25 countries due to data availability.[19] The data has been gathered from the following sources: prices and subscription number variables are from the EMC mobile telecommunications database, and demographic and infrastructure data is taken from the OECD Telecommunications Database 2001. Additional data on country characteristics was taken from the WDI World Bank database. The variable definitions and their descriptive statistics can be found in Table 1.

Dependent variables

Our dependent variable in the entry equation is the entry decision (ENTRY) and the *year in which positive usage numbers are first reported*. In our panel of countries therefore, a country-year observation gets value zero if entry has not yet taken place and one when the number of 2G subscribers in a country is positive for the first time.

The variable L_DIFF measures (log) diffusion of digital mobile phones[20] per capita using the diffusion measure of equation (4). The price variable (PRICE) is the (log) average monthly cost of 120 minutes peak calls (in USD and PPP).[21] The probit

[19] The following countries listed in Figure 1 are excluded from the estimations: Hong Kong, China, Singapore, Brazil, Venezuela and Chile.

[20] Information is given on the number of subscribers (i.e. monthly contracts) for each active digital network (technology) in the country – i.e. GSM, CDMA, TDMA and PDC.

[21] Some remarks about the quality of our price data are appropriate. While the average price of a particular price schedule is not a perfect measure of industry prices, especially given the wide variety of pricing schemes, we still believe it to be a reasonable proxy (and the best available) for the prices consumers face. We experimented with other call intensities (60min, 300min), monthly subscription

model correcting for potential sample selection bias is estimated by using the dummy variable DIG_D – which is 0 when there are no digital wireless services available in a country and 1 if there are – as dependent variable.

Regulatory and competition variables

We include a set of dummy variables on the nature of domestic competition and standardization (see Table 1 for the description of variables and Section 3 for a discussion on their expected effects).

Our two main policy variables are STAND and COMP. STAND takes value 1 if the country has mandated a technological standard for 2G telecommunications. COMP proxies for competition by taking value 1 if there are at least two active providers of 2G services in a country and year.[22,23]

The regulatory environment is captured by INDEP, where INDEP = 1 if the telecoms market is regulated by an independent regulatory authority and 0 otherwise.[24] It is often said that independent regulators can regulate a market more efficiently than

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rates and cost per three-minute call but found the results to be qualitatively very similar. Nevertheless, our results would be biased if (i) there were other costs faced by the consumer that vary across countries in a systematically different way from call prices or (ii) if the popularity of different pricing schemes would have changed dramatically over time. A prime suspect for (i) are (typically subsidized) handset prices, but we found no evidence that subsidization strategies varied systematically across countries. Interviews with industry experts suggest that within the menu of monthly contracts, the distribution has remained relatively stable, while the proportion of pay-as-you-go users (not captured in our diffusion and pricing variables) has increased over time. If anything then, our results understate the diffusion of mobile telephony and overstate the average prices paid by consumers.

[22] We also experimented with a further policy variable capturing the use of the receiver-party-pays (RPP) principle. RPP was only used in three countries (USA, Canada, Mexico (until 1999) in our sample however, so that the country dummies of these three countries and the RPP variable are highly correlated, which makes simultaneous estimation impossible. However, the country dummies of the three countries carry strong negative signs, and including the RPP variable in place of the country dummies confirms the intuition that RPP led to slower diffusion.

[23] We treat policy variables as exogenous determinants of diffusion and pricing – as previous empirical studies on the telecommunications industry – but, as pointed out by an anonymous referee, it would be an interesting extension to our study to investigate potential endogeneity of various telecommunications policy instruments. Unfortunately, our data lacks reliable instrumental variables for this purpose.

[24] There are basically two types of regulatory authorities: Independent regulatory authorities and government departments acting as regulators. While this is a somewhat crude measure of the nature of a regulator, the focus in our paper is on regulatory outputs (i.e. market parameters that have been set) rather than inputs (i.e. nature and setup of the regulatory process).

those being part of a ministry. Wallsten (2001) points out that independent regulators are more likely to initiate regulatory reforms, and independent regulators are expected to experience fewer conflicts of interest, especially since lobbying efforts by mobile operators cannot be made via the government. The potential influence of the incumbent on the regulator may therefore be weaker when the regulator is independent. Since the delay of 2G introduction chiefly benefits incumbents trying to avoid possible cannibalisation of their existing services, an independent regulator is expected to accelerate the timing of 2G introduction. If an independent regulator indeed creates a more efficient market environment, we also expect prices to be lower and diffusion to be faster in countries with independent regulators.

Endogenous variables

The estimated system of equations includes two endogenous explanatory variables. First, PRICE is an endogenous explanatory variable in the diffusion equation – since technology diffusion is the aggregate of a large number of consumers' cost-benefit decisions, prices should be negatively related to diffusion.

Second, we assume that the timing of entry into the 2G market is a key strategic decision factor of wireless operators. We therefore treat the inverse Mills ratio (MILLS) obtained from our Heckman selection equation as an endogenous variable in the estimated system of equations.

Control variables

The installed base of previous vintage(s) of a network technology is likely to affect the timing of market introduction of subsequent vintages (Farrell and Saloner 1985). As mentioned before, 1G profitability is a likely indicator for expected 2G profits. Also, learning-by-using effects increase the profitability of adopting technologies based on the previous vintages of technologies.[25] Finally, since analogue mobile telephony was much less efficient in its spectrum use, spectrum capacity constraints were likely to necessitate the transition to 2G. We therefore assume that the installed base of 1G users, L_A_IBASE, triggers earlier entry.

Two important effects in the adoption of new technologies are the *network* and the *epidemic* effects captured by a time trend variable (TIME) that unfortunately does not allow us to distinguish the order of magnitude of each effect separately.[26] Both state that as more consumers are using a technology, an increasing rate of non-users become users. Network effects exist if the product becomes more useful, e.g. due to lower intra-network call rates, while epidemic effects arise from informational diffusion and reduction of uncertainty (Bikhchandani et al. 1992). The installed base may also be related to mobile service prices, since a greater number of previous users implies benefits from technological progress and scale or learning economies in manufacturing and service provision and thus lower service prices.[27]

The presence of a domestic manufacturer of complementary goods may have a twofold effect on the timing of entry: first, they provide information on the technology to the regulator, thereby increasing pressure on incumbents to introduce 2G. Second, they frequently collaborate with the operators themselves in order to gauge their likely needs and therefore make entry more attractive to incumbents as

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[25] Similar evidence on the mobile market has been found by Liikanen et al. (forthcoming). For intergenerational effects in other industries, see Stoneman (2002), Chapter 9 and references therein.

[26] There is a large literature going back to Griliches (1957) that studies the epidemic effect in technological diffusion. Network effects have been identified by Koski (1999) in a diffusion setting, and by Saloner and Shepard (1995) in the context of first adoption of a new technology.

[27] In the price equation, we also used a variable measuring the (log) number of mobile phone users per capita, to control for the installed base effect. This explanatory variable was, however and as expected, highly correlated with the policy variables of our interest, particularly competition. Therefore, we ended up excluding the installed base variable, which is also highly correlated with TIME, from the model.

well.[28] We construct a variable MANUF that takes on value 1 if there is a domestic complementary goods manufacturer (0 if there is not) and we expect it to have a positive effect on the timing of entry. Alternatively, we use the level of ICT investment per head (ICT_POP) as a proxy for the propensity of a country to invest in new ICT technologies.

We also have to account for the relative (per-person) cost of building a network. Mobile networks operate through a network of transmission towers covering a limited geographical area (or cell). Therefore, the population density (POP_DENSE) or the degree of urbanization (URBAN) of a country provides a proxy for the per-subscriber cost of setting up a network.[29] Lower population density or urbanization may however also have a reverse effect since mobile communication may be more useful in such markets because people spend more time travelling (i.e. away from a fixed telephone) and will require a means of communication in an emergency. The expected profitability and demand in a sparsely populated economy may therefore be higher and introduction may take place earlier. The results of our estimations allow us to assess the net effect of the two.

The wealth of a country will influence the demand for, and the prices of, mobile services. We assume that both the *level of wealth* (variable GDP/POP – that is, (log) gross national product per capita) and GDP (per capita) growth (variable GDP_G, annual % growth of GDP per capita) accelerate entry time and are positively related to mobile phone diffusion and service prices. We also assume that the timing of 2G introduction may depend on the state of the ICT development of a country and control

[28] For example, Nokia's collaboration with incumbent Finnish ICT firms is widely documented (Ali-Yrkkö 2001)

[29] Note that this would not be a valid proxy for setup costs if mobile operators decided to service only part of the country. While this was common for 1G networks, 2G operators achieved almost universal coverage already in early stages of their rollout, to a large part in expectancy of high diffusion rates later on.

for this by the number of fixed lines per head (FIX_POP) in the entry equation. Another control variable that may affect 2G entry is the price of fixed-line services.

Instruments

We use a constant term and all exogenous variables as instrumental variables in the system of price and diffusion equations. Also, we assume that all variables affecting entry (e.g. a country's population density) may indirectly contribute to diffusion and prices via endogenous variables. We thus use also the explanatory variables of the sample selection equation as instruments.

5. Empirical findings

We study three related phenomena. First, we estimate a hazard rate model that looks at the timing of launching 2G. We then simultaneously estimate two equations: the diffusion and the pricing of 2G services, while controlling for sample selection,[30] as explained above.[31] We thus give a rather complete picture of the evolution of the mobile telephony industry in different countries. We also estimate a random effects model for mobile diffusion – which is typically used in previous empirical studies – to illustrate our contribution to the empirical literature on technology diffusion.

(i) Entry of 2G services

The results of our hazard rate model of entry timing are reported in Table 2. Since parameter values for the monotonically changing hazard rate in the Weibull specification are strongly significant, we select the Weibull specification throughout

[30] The estimates of the inverse Mills ratio are obtained from the estimation of the probit model of market entry that includes the same explanatory variables as the hazard rate model for the timing of entry.
[31] Estimating all three decision equations simultaneously was not possible due to the relatively small sample size and the resulting convergence problems.

and report results accordingly.[32] We assume that 2G was only available and (potentially) commercially viable in the year prior to the first introduction (1991). All of our sample countries adopt 2G within the time period considered, which avoids problems of right-censoring.

Our empirical specification of equation (2) is then as follows:[33]

$$prob(E_{it} = 1) = \gamma \cdot t^{\gamma - 1} \cdot \exp\begin{pmatrix} a_0 + a_1 STAND_i + a_2 INDEP_{it} + a_3 COMPF_{it} + \\ + a_4 L\_A\_IBASE_{it} + a_5 MANUF_i + a_6 POP\_DENSE_{it} + \\ + a_7 FIX\_POP_{it} + a_8 GDP/POP_{it} + \varepsilon_{it} \end{pmatrix}$$

Countries are assumed to learn from previous adoption decisions (Dekimpe et al. 1998). We would therefore expect the hazard of entry to exhibit positive duration dependence, i.e. $\gamma > 1$, since there are more countries to learn from (the number of countries that have adopted 2G is a non-decreasing variable), and learning may simply take place over time.

We experimented with models substituting population density with the degree of urbanization (column 2.II) and using ICT_POP in place of the MANUF dummy (column 2.III). Combinations of the various covariates have been tried, but not reported.[34]

STAND generally has a strong and positive effect on the timing of entry. The coefficient varies across specifications, but is strongly positive. Independently regulated (INDEP) countries do not enter (statistically) significantly earlier.[35] On the

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[32] Alternative specifications of the baseline hazard we experimented with were exponential and Cox proportional hazard models. The nonparametric estimate of the baseline hazard is monotonically increasing, as expected from our Weibull results.

[33] We estimated the hazard model of entry using STATA, Release 6. The routines for parametric survival-time models (streg) are found in the reference manual, pp. R427-434.

[34] These results are available from the authors.

[35] Note that we are controlling for two potential outputs of the regulatory process, standardization and the degree of competition in wireline services. Our results suggest that other regulatory policies associated with an independent regulator do not result in significantly earlier entry times.

other hand, the degree of competition in wire-line markets (COMPF) is a statistically significant accelerator of 2G entry, as is the diffusion of 1G cellular (L_A_IBASE) in two of our specifications. The strength and significance of these results suggests that incumbents do indeed sacrifice fixed-line revenues for 2G revenues, and that there exists considerable complementarity between 1G and 2G. The existence of a major mobile equipment manufacturer (MANUF) has a consistently positive effect and is marginally significant in our preferred specification. Anecdotal evidence suggests that mobile manufacturers cooperated very closely with domestic operators, thus initiating a supply push to start the market. This effect is not present when substituting MANUF with ICT_POP, suggesting that it is the presence of a major firm rather than the sheer intensity of investment in telecommunications that plays a role in the entry decision. Higher population density (POP_DENSE) seems to slow down the entry of 2G, which may appear counterintuitive at first. We have to keep in mind however that the coefficient is likely to be the net effect of setup costs per-subscriber and the expected strength of demand. Our results suggest that the second effect dominates, i.e. that lower population density renders mobile telephony more useful, ceteris paribus.

Finally, the number of fixed lines per head (FIX_POP) and a country's wealth (GDP/POP) are important control variables of differences in country developments (the precision of the other coefficients decreases considerably when omitting them), but they are not significant factors for explaining the entry of 2G technology.

A final noteworthy point is the strong and positive duration dependence of the entry hazard. In other words, the hazard rate is increasing monotonically, which is an indicator that countries either learn from each other over time or that there is another exogenous process that facilitates entry.

(ii) Diffusion and price dynamics

Our results are reported in Table 3. All specifications include country dummies that are not reported. The first column of the table reports the estimation results of the random effects model for diffusion.[36] This model is used as a reference point as it represents empirical diffusion models used in previous empirical studies that have excluded potential sample selection bias in diffusion equation. Unlike the 3SLS model, the random effects model treats price as exogenous variable.

In the three stage least square (3SLS) models our price and diffusion equations (5) and (6) are estimated simultaneously by using the instrumental variable (IV) method, in which part of the explanatory variables may be endogenous/pre-determined and all the parameters of the model are estimated jointly (Berndt et al. 1975; Greene, 2003, pp. 405-406).[37] The advantages of the 3SLS IV method are that it allows the error terms of the price and diffusion equations to be correlated and it allows us to treat various factors such as prices in the diffusion equation as endogenous.[38]

To take into account potential sample selection bias (discussed in the previous section), and to test its existence, we used the ideas of Heckman's two-stage sample selection approach (1979)[39] (see also equation 5 and related discussion).[40]. To

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[36]These estimation results are obtained by TSP 4.5 software. For the specifics of the random effects model (estimated with VARCOMP command of TSP) and further references and estimation commands, see TSP 4.5 Reference Manual Version 4.5, pp. 201-204.

[37] We use TSP 4.5 software to obtain 3SLS IV estimation results. For estimation commands, see TSP Reference Manual Version 4.5, pp. 283-284. Standard errors are computed from heteroscedastic-consistent matrix (Robust-White), using "ROBUST" command in TSP.

[38] Single equation panel data models used in previous studies of mobile diffusion have not used endogenous explanatory factors.

[39] We should note here that several features of our 3SLS IV model deviate from the traditional two-step model of Heckman and that our model of the effects of sample selection on diffusion does not rigorously follow the traditional (simple linear) approach. For instance, we have not adjusted the standard errors for the estimated coefficients of diffusion and price equations. These type of modifications are complex in the case of our model – unlike in the case of the simple linear model (see Greene, 2003, pp. 784-785) - and subject of future research. For the purposes of this paper, we wanted to obtain a sensible control for selection for exploration of the effect of selection on the diffusion process.

[40] Empirical findings concerning the timing of 2G entry are discussed above so we do not discuss here the estimation results of the probit model that we use to create an additional explanatory variable correcting for potential sample selection bias, the inverse Mills ratio variable (MILLS).

evaluate the importance of the inclusion of the endogenous MILLS variable, we estimate a model first *without* the inverse Mills ratio variable. As a next step, we estimate the following simplified system of equations:

$$L\_DIF_{it} = b_0 + b_1 TIME + b_2 PRICE_{it} + b_3 REG_{it} + b_4 GDP/POP_{it} + \\ + b_5 GDP\_G_{it} + b_6 MILLS_{it} + \eta_{it}$$

$$PRICE_{it} = c_0 + c_1 TIME + c_2 REG_{it} + c_3 GDP/POP_{it} + c_4 GDP\_G_{it} + c_5 MILLS_{it} + \mu_{it}$$

where REG is a vector of regulatory or policy variables of our interest. REG contains the standardization (STAND), competition (COMP), multiple entrants (MULTIE) and independent regulator (INDEP) dummy variables.

The estimation results of the random effects model are very similar in regard to our key policy variables, standardization and competition, to those found by previous studies: standardization is statistically insignificant, whereas competition is positively and statistically significantly related to mobile phone diffusion.

Comparing the estimation results with and without correcting for potential market entry bias suggests that endogenous entry clearly affects diffusion dynamics. First, various coefficients in the diffusion equation are estimated more accurately when MILLS is included. For instance, when differences in entry are not controlled for, the price variable is not statistically significant in the diffusion equation, an unlikely result. Second, the MILLS variable is itself statistically significant. Indeed, the estimated coefficients of the explanatory variables of diffusion equation seem to be biased unless we control for market entry. In other words, cross-country differences in commercialization of 2G mobile telephony are systematically determined by various factors such as the order of magnitude of competition in fixed-line telephony.

The estimated coefficient of MILLS variable is statistically significant (at p=0.05) also in the price equation. The positive coefficient of the Mills variable in both the price and diffusion equation implies that there is positive correlation between the error terms of sample selection equation and diffusion/price equation. This indicates that countries that have not yet commercialized 2G services at any given time are more likely to have lower (expected) levels of digital mobile phone diffusion and service prices, i.e. less profitable 2G markets, than those that have entered relatively earlier.[41] These systematic cross-country differences in market profitability and entry times seem to clearly affect the estimates of our policy variables of interest and justify the use of the empirical model correcting this bias.

The estimation results of the 3SLS model while controlling for the sample selection bias show that PRICE slows down the diffusion of mobile phones as expected. STAND clearly facilitates the diffusion of mobile phones, which suggests that technological compatibility increases the expected user value of mobile services, resulting in quicker diffusion. Interestingly, the estimates of the random effects model suggest that variable STAND is not significant in the diffusion equation. This finding is consistent with the estimation results on digital mobile telephony in GV 2001. It thus seems that the statistical significance of STAND in the diffusion equation depends crucially on controlling for sample selection bias as well as endogenous prices.

We also find that STAND carries positive and significant signs in the pricing equation. It thus appears that competition between incompatible standards – a standards battle – triggers more intense price competition, whereas firms follow less aggressive pricing strategies when competition takes place within a single standard. This confirms that operators will value a large installed base higher if the switching

[41] As the estimation results of the hazard model show, both country-specific historical market evolution (i.e. diffusion of analogue mobile phones) and competition policy in telecom markets (i.e. degree of competition in fixed-line services) have been important determinants of the profitability of 2G wireless markets and market entry.

cost to a rival incompatible network are higher, and they consequently price more aggressively. This finding contradicts the commonly held view that compatible products are closer substitutes which implies more intense competition in standardized markets. We expect this effect to obtain in later stages of market development.

The coefficient of the competition variable COMP carries the expected sign (when significant) but is not statistically significant in the 3SLS diffusion model including MILLS. It seems that when the variables capturing endogenous prices and entry are properly controlled for, including a competition dummy does not provide any significant additional information explaining cross-country variation in the diffusion of mobile phones. The estimated coefficient of variable COMP is negative and statistically significant in the price equation as expected. These findings suggest that competition has primarily facilitated mobile phone diffusion via its impact on service pricing and that non-price competition has played a minor role in (at least, directly) promoting diffusion.

The dummy variable MULTIE, i.e. whether or not the 2G market was competitive from its very beginning, seems to have a strong positive influence on both diffusion and prices, even after controlling for competition at any point in time (COMP). It thus seems that wireless service pricing has been less aggressive in countries that had immediate competition early on. Our results thus lend support for the hypothesis of monopoly penetration pricing in the 2G market. The positive sign of MULTIE suggests that the diffusion of digital mobile telephony has been faster in markets that were competitive from the outset, perhaps due to increased non-price competition.

In summary, our empirical findings indicate that between-firm competition affects mobile diffusion as expected, speeding up diffusion, whereas between-standards competition hinders mobile phone diffusion although it results, on average, in lower prices. It is difficult to evaluate whether the apparent direct consumer benefits of standardization evident in more rapid diffusion exceed the economic costs arising from higher prices in a standardized market.

The variable INDEP generally fails to explain diffusion dynamics in the 2G markets and neither does it appear as a statistically significant explanatory variable in the pricing equations. Further analysis using a more sophisticated measure of the independence of the regulator is required to shed further light on the relationship between the type of regulatory authority and market performance in the telecommunications sector.

The positive and statistically significant coefficient of the time trend variable suggests that network and epidemic effects strongly influence diffusion dynamics of network technologies, which confirms the findings of previous studies. In the price equation, the estimated coefficient of the time trend is not statistically significant, which supports the notion that cost-improving technological progress was less important than demand-side effects such as network or epidemic effects.

Our estimation results also capture the expected positive relationship between the level of wealth, or GDP per head, and diffusion. GDP/POP is positively and statistically significantly related to mobile service diffusion as expected. Higher GDP/POP seems to also imply higher service prices. Change in GDP per capita (GDP_G) do not however explain variation in wireless diffusion and service prices.

6. Conclusions

We study the effect of standardization and competition on the evolution of the 2G mobile industry along three dimensions: entry timing, service prices, and diffusion speed. We find that standardization significantly accelerates 2G entry and diffusion, although price competition is less aggressive within than between standards. Our results also suggest that an early monopolist will price more aggressively to build up an installed base. We also find that liberalizing markets for incumbent technologies (i.e. fixed line telephony) accelerates the commercialization of 2G.

By explicitly recognizing the linkages and (partial) endogeneity of the three dimensions, we are able to offer a more complete picture of the evolution of a new market. In particular, our empirical study raises the issue of non-random selection arising from cross-country differences in the timing of commercialization of new technologies. Our empirical exploration shows that this type of sample selection may, indeed, be a substantial problem in the cross-country studies on technology diffusion and cause biased estimates of the policy variables of interest. Further empirical work along these lines is needed to assess the generalizability of our results.

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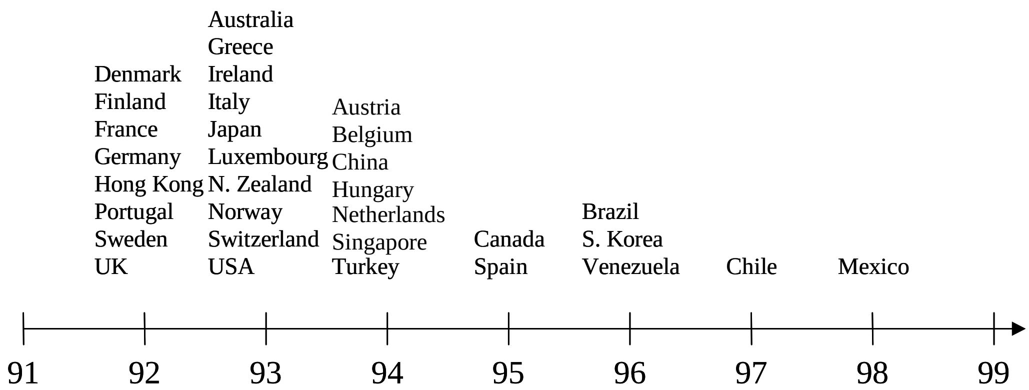

Figure 1: Timeline of 2G introduction dates

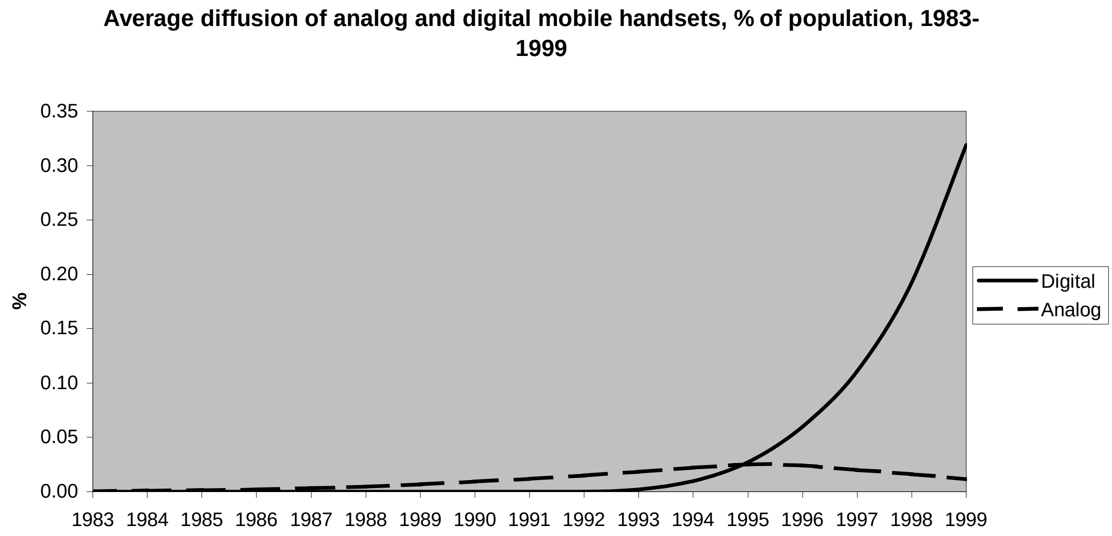

Figure 2: Average diffusion of analogue and digital mobile handsets

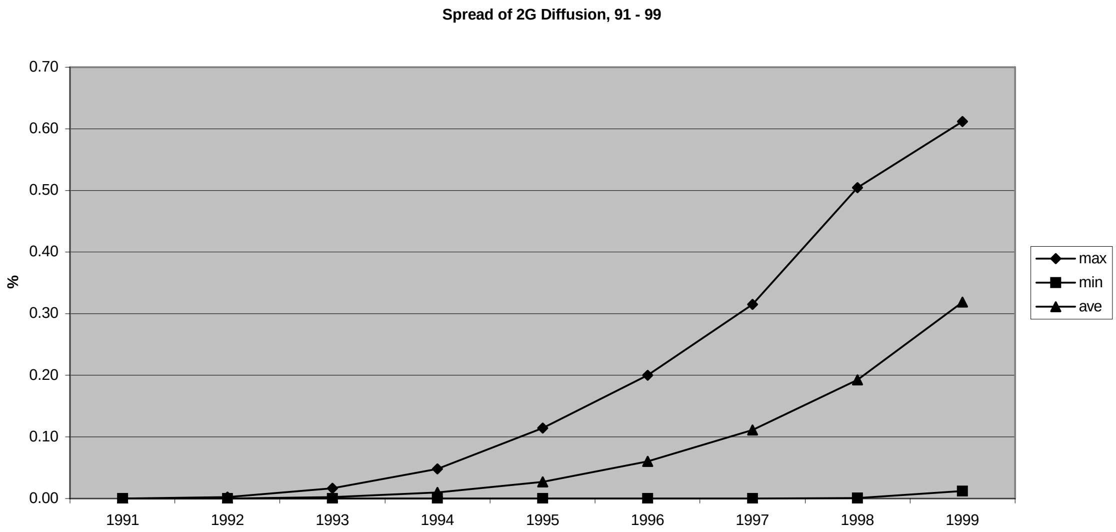

Figure 3: Spread of 2G diffusion rates, 91 – 99

Table 1. Descriptive statistics

Name	Description	Mean	S.D.
Dependent Variables			
ENTRY	Dummy variable = 1 if entry takes place in that year, 0 otherwise	.271	.446
PRICE	(Log) monthly cost of 120 minutes peak calls (in USD, PPP)	6.857	2.592
L_DIFF	(Log) (# 2G mobile phones/population)/(1-(# 2G mobile phones/population))	-2.407	1.983
DIG_D	Dummy variable = 1 if there are digital wireless services available in a country, 0 otherwise.	0.406	0.492
Regulatory and Competition Variables			
COMP	Dummy variable = 1 if # 2G competitors > 2, 0 otherwise.	0.884	0.321
MULTIE	Dummy variable = 1 if # 2G competitors in first year of 2G service > 2, 0 otherwise.	0.749	0.435
STAND	Dummy variable = 1 if country has one 2G standard, 0 otherwise.	0.810	.394
SHARE	(Log) market share of dominant 2G standard	-0.053	0.175
COMPF	(COMPLO+COMPLD+COMPI)/3, where COMPLO, COMPLD, COMPI = 1 if local/long-distance/international telecoms services are not monopolies, 0 otherwise.	0.491	0.492
INDEP	Dummy variable = 1 if telecom sector is regulated by independent regulatory authority, 0 otherwise.	0.293	0.456
Control Variables			
L_A_IBASE	(Log) number of analogue/1G mobile phones per capita.	-5.188	2.468
L_D_IBASE	(Log) Number of mobile phones per capita.	-2.212	1.102
MANUF	Dummy variable = 1 if country is headquarter to a major manufacturer of ICT products.	.171	.015
ICT_POP	Total ICT investment in USD per capita.	738.035	652.833
POP_DENSE	Inhabitants per sq.km	363.202	1153.066
URBAN	Percentage of people living in urban areas	24.813	0.812
GDP/POP	(Log) gross domestic product per capita.	9.839	0.652
GDP_G	% growth of GDP per capita	.016	.107
FIX_POP	Number of fixed lines per capita.	41.110	15.510

Table 2. Estimation results of the entry model

	2.I	2.II	2.III
STAND	2.525**	1.352*	3.289**
	(.645)	(.754)	(.939)
INDEP	-.322	-.048	-1.277
	(.664)	(.916)	(.771)
COMPF	2.988**	2.284*	3.549**
	(.535)	(.896)	(.830)
L_A_IBASE	.108*	.129*	.055
	(.045)	(.051)	(.051)
MANUF	1.188*	.403	
	(.491)	(.698)	
ICT_POP			.001
			(.001)
POP_DENSE	-.005**		-.004**
	(.001)		(.001)
URBAN		-.027	
		(.024)	
FIX_POP	.040	.057	.033
	(.037)	(.038)	(.033)
GDP/POP	-.083	-.423	-.709
	(.563)	(.544)	(.576)
CONST	-4.961	.400	-.858
	(4.324)	(3.992)	(3.997)
log(γ)	2.926**	2.772**	2.901**
	(.363)	(.317)	(.356)
Log Likelihood	-9.358	-11.630	-9.934
Wald χ^2	101.07	60.91	69.09
OBS (yr*ctry)	62	62	60

Note: * denotes significance at p=0.05; ** denotes significance at p=0.01.
Standard errors in parentheses.

Table 3. Estimation results for Diffusion/Pricing Model[1)]

Diffusion	Random Effects	3SLS	3SLS with IMR[2)]	**Pricing**	3SLS	3SLS with IMR[1)]
CONST	-1630.7**	-1606.3**	-1766.4**	CONST	29.85	26.1
	(37.43)	(52.58)	(108.18)		(35.09)	(61.53)
MULTIE	3.192	.776	10.857**	MULTIE	10.258**	12.457**
	(1.759)	(2.846)	(5.269)		(.729)	(1.115)
PRICE	-.194	.279	-.842**			
	(.116)	(.237)	(.351)			
STAND	2.847	.403	11.752*	STAND	9.820**	12.537**
	(1.630)	(2.683)	(5.106)		(.626)	(1.075)
COMP	0.600**	0.817**	-0.040	COMP	-.335**	-.458*
	(.157)	(.160)	(.402)		(.118)	(.227)
INDEP	-.101	-.023	-. 836	INDEP	-.094	-.523
	(.160)	(.160)	(.534)		(.120)	(.297)
GDP/POP	1.256**	2.224**	2.467*	GDP/POP	.063	1.323*
	(.373)	(.416)	(1.220)		(.274)	(.556)
GDP_G	.134	-.723	-2.094	GDP_G	0.598	-1.145
	(.368)	(.516)	(1.195)		(.419)	(.760)
TIME	.808**	.791**	.868**	TIME	-.018	.003
	(.020)	(.027)	(.054)		(.018)	(.031)
MILLS			1.612**	MILLS		.866*
			(.643)			(.393)
OBS	486	160	160		160	160
R^2	.953	.938	.842		.983	.970

Note: * denotes significance p=0.05; ** denotes significance at p=0.01. Standard errors in parentheses.
1) All specifications include country dummies that are not reported. We note here that the 3SLS model comprises time-invariant country-specific effects, whereas the random effects model includes an additional country-specific random disturbance term to account for country-specific heterogeneity.
2) IMR= Inverse Mills Ratio.