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Centre for Economic Policy Research
90–98 Goswell Rd, London EC1V 7RR, UK
Tel: (44 20) 7878 2900, Fax: (44 20) 7878 2999
Email: cepr@cepr.org, Website: http://www.cepr.org

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ABSTRACT

The Diffusion of Mobile Telecommunications Services in the European Union*

We study the determinants of the diffusion of mobile telecommunications services in the European Union in a logistic model of technology diffusion. We find that the transition from the analogue to the digital technology during the early nineties, and the corresponding increase in spectrum capacity, has had a major impact on the diffusion of mobile telecommunications. The impact of introducing competition was also significant, during both the analogue and the digital period, though the effect was proportionately smaller. Finally, we find that countries which granted first licenses at later points in time, show a significant catching-up effect, though international convergence may be expected only by the year 2006. The empirical results remain robust when other possible determinants of diffusion are included, such as the size of the fixed network and GDP per capita.

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Harald Gruber
Projects Directorate
European Investment Bank
Boulevard Konrad Adenauer
L–2950 Luxembourg
LUXEMBOURG
Tel: (352) 4379 8606
Fax: (352) 4379 8831
Email: gruber@eib.org

Frank Verboven
Department of Economics
University of Antwerp (UFSIA)
Prinsstraat 13
B–2000 Antwerpen
BELGIUM
Tel: (32 3) 220 4877
Fax: (32 3) 220 4799
Email: verboven@ufsia.ac.be

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NON-TECHNICAL SUMMARY

Technological innovation *per se* is not sufficient to achieve economic growth and increased welfare. Once a new technology has been invented, further progress depends on the speed at which the new technology is introduced and diffused. A general theme that emerges from the large literature is the striking heterogeneity in the speed of introduction and diffusion across sectors. Despite the large amount of research on the adoption of new technologies, the determinants of diffusion remain only partially understood.

Mobile telecommunications services provide an interesting case on how several successive events have affected the diffusion pattern. The technology of wireless communications has been available since the early 1960s. The adoption of the wireless telecommunications became only feasible on a large scale in the early 1980s, however. The subsequent introduction and diffusion of mobile services was affected by further technological and regulatory developments. An important technological development was the transition from the analogue to the digital technology, which considerably increased spectrum capacity. Regulatory developments concerned government decision with respect to the coordination to a common standard. The introduction and the timing of first licenses granted and the introduction of additional competition through second or third licenses were other important regulatory issues, which were resolved quite differently in the different countries of the European Union.

This paper aims to unravel the determinants of the diffusion of mobile telecommunications in the countries of the European Union. Understanding the diffusion of mobile telecommunications is important in light of the recent drastic developments. The sector is by far the most dynamic sector in telecommunications, with annual revenue growth rates in excess of 30% for the last three years, reaching a market size of 21 billion ECU for the European Union. In 1997, the number of new subscribers increased by 57%, yielding a European average penetration rate of 14 mobile phone subscribers per 100 inhabitants. In Finland, the penetration rate has even reached 50%.

A central question is whether the diffusion has been largely driven by technological innovation, or whether, government licensing policies have also had a significant impact. The sample of European countries is informative because of the large differences in policies that have been followed. Using panel data on the whole history of the industry for all members of the European Union, a logistic model of diffusion is estimated, accounting for international differences in policies. The paper addresses the relative importance of three main factors: technology (analogue versus digital); the timing of the first licenses granted by the government (and the possibility of catching up by late coming countries); and the introduction of additional competition (monopoly versus oligopoly). In addition, the impact of the existing fixed line network (substitute or complement) and GDP *per capita* is considered.

Intuitively, the technological developments and the implied changes in capacity and quality may explain global increases in the number of mobile subscribers, common to all countries. In contrast, the decisions taken by the local governments, regarding the timing and the number of licenses granted, may explain why in some countries the diffusion occurred more rapidly than in other countries. During both the analogue and the digital area, there have been periods of monopoly and periods of (duopoly) competition, and competition was not introduced at the same time in all countries. Furthermore, during the early years there were even countries without any supplier.

Our empirical results indicate that some 60% of the total population will eventually adopt mobile telecommunications. We find that the transition during the early nineties from the analogue to the digital technology and the corresponding increase in spectrum capacity has had a major impact on the diffusion of mobile telecommunications. Apparently, the technological developments induced even monopolist operators to reduce their prices and attract more adopters. Nevertheless, the impact of introducing competition was also significant, though the effect was proportionately smaller as compared with the technology effect. Competition played a more prominent role during the analogue period, which is possibly due to the considerably higher prices during the analogue period. No evidence of pre-emptive behaviour by incumbents could be found. Finally, countries which granted licenses at a later point in time show a significant catching-up, though international convergence may be expected only by the year 2006. The results remain robust when other determinants of diffusion are included. The fixed network seems to be perceived as a substitute for the mobile network and GDP *per capita* seems to have a positive effect. The role of these effects, however, has to be interpreted with some caution because of multicollinearity problems.

The results involve a wide range of policy issues – including the role of technology, the timing of first licenses and the introduction of competition. The importance of improvements in technology appears clear and hard to underestimate. The role of the timing of first licenses demonstrates that early countries have a fairly long persisting lead (until the year 2006). As indicated by other studies, the welfare costs associated with such a persistent delay may be quite high. Finally, the relatively small estimated effect of competition should be put in perspective. First, the sample covered mainly movements to duopoly. The effects of even more competition remain to be seen as further licenses are being issued. Second, even if competition has a relatively small effect on the adoption decision by consumers this does not imply similar effects on the usage decision.

These qualifying statements call for various interesting directions in future work. For example, detailed price data (which is not an obvious task) may be collected to achieve further results on the differences between monopoly behaviour and competition. The role of the local policies followed in the various countries may be studied in further detail to obtain additional insights on the differences in adoption levels and speeds across countries. Finally, the evolution during the next ten years, when the industry will have reached a stage closer to maturity, will yield interesting new data against which the results of this paper can be confronted.

1. Introduction

Technological innovation *per se* is not sufficient to achieve economic growth and increased welfare. Once a new technology has been invented, further progress depends on the speed at which the new technology is introduced and diffused (Grossman and Helpman, 1991). There has been a large amount of research on the adoption of new technologies. A general theme that emerges from this work is the striking heterogeneity in the speed of introduction and diffusion across sectors. In the semiconductor industry, for example, the adoption of new technologies is extremely rapid (Gruber, 1994). In other sectors, innovations spread at a much slower pace, many years after the technological innovation became first available (Ray, 1984). Despite the large amount of research on the adoption of new technologies, the determinants of diffusion remain only partially understood.

Mobile telecommunications services provide an interesting case on how several successive events have affected the diffusion pattern. The technology of wireless communications has been available since the early 1960s. However, only after basic innovations in semiconductor technology (such as the microprocessor), the adoption of the wireless telecommunications became feasible on a large scale (Garg and Wilkes, 1996). The subsequent introduction and diffusion of mobile services was affected both by further technological innovations, such as the transition from the analogue to the digital technology, and by regulatory decisions by the government concerning spectrum licensing, the introduction of additional competition and the co-ordination to a common technical standard (Rappaport, 1996).

The aim of this paper is to unravel the determinants of the diffusion of mobile telecommunications in the countries of the European Union. A central question we ask is whether the diffusion has been largely driven by technological innovation, or whether in addition regulatory licensing policies have had a significant impact. The sample of European countries is informative because of the large differences in policies that have been followed. Using panel data on the whole history of the industry for all members of the European Union, a logistic model of diffusion is estimated, accounting for international differences in policies. The paper addresses the relative importance of three main factors: technology (analogue vs. digital), the timing of the first licenses granted by the government (and the possibility of catching up by late coming countries), and the introduction of additional competition (monopoly versus oligopoly). In addition, the impact of the existing fixed line network (substitute or complement) and GDP per capita is considered.

We find that the transition from the analogue to the digital technology during the early nineties, and the corresponding increase in spectrum capacity, has had a major impact on the diffusion of mobile telecommunications. The impact of introducing competition was also significant, during both the analogue and the digital period, though the effect was proportionately smaller. Finally, we find that countries which granted first licenses at later points in time, show a significant catching-up effect, though international convergence may be expected only by the year 2006.

Understanding the diffusion of mobile telecommunications is important in light of the recent drastic developments. The sector is by far the most dynamic sector in telecommunications, with annual revenue growth rates in excess of 30% for the last three years, reaching a market size of 21 billion ECU for the European Union. In 1997, the number of new subscribers increased by 57%, yielding an European-average penetration rate of 14 mobile phone subscribers per 100 inhabitants. In Finland, the penetration rate has even reached 50%.

A recent, related paper is by Parker and Röller (1997) on the mobile telephone industry in the U.S. In a structural oligopoly model, they focus in more detail than we do on aspects of competition, but they abstract from the other dynamic questions that we address. Interestingly, Parker and Röller find that the change from monopoly to duopoly in U.S. states had a significant, though relatively small effect on the degree of price competition because of collusion. This result has remarkable similarities with what we find in our quite different diffusion framework for the countries of the European Union, where the effect on diffusion coming from the increased capacity due to technological innovations has been much stronger than the effect from increasing the number of firms.

Section 2 presents the background technological and regulatory developments in the market for mobile telecommunications services. Section 3 describes the econometric model of diffusion, suitably adapted for a cross-country analysis. Section 4 presents and discusses the empirical results. Section 5 concludes and provides implications for public policy.

2. The evolution of the market for mobile telecommunications services

Mobile telecommunications is a relatively new technology for communication networks. Its characteristics offer opportunities to change the traditional monopoly structures of the telecommunications sector and to speed up the deployment of alternative telecommunication infrastructures. This section describes both the technological and the political/regulatory developments that are of potential importance in understanding the evolution of the market and the speed of technology diffusion.

2.1. Technological developments

Generally speaking, there are two basic ingredients in a telecommunications network: transmission capacity and switching. In both areas, there have been enormous declines in costs during the last two decades (ITU, 1995, chapter 5). The introduction of fibre optic cables has lead to virtually unlimited transmission capacity; the cost of computer electronics to operate fibre transmission has been decreasing at an annual rate of about 10 percent during the last decade. Switches have also experienced significant technological changes. Modern switches are like computers and their economics is basically that of semiconductors. This means they benefit from roughly the same performance increases, i.e. a double in power every 18 months according to Moore's law, and a price fall along the learning curve (Gruber, 1994).

In a mobile communications network, radio transmission replaces the physical connection between the user and the base station, the antenna that constitutes the first physical link with the network. The investment cost of connecting a mobile subscriber is therefore cheaper[1]. The scarce resource required for radio transmission is the spectrum. Due to technological progress, capacity constraints from spectrum scarcity have been gradually reduced and transmission quality improved (see, for example, Rappaport, 1996). The first generation analogue systems of the early 1980s use portions of the spectrum around the 450 MHz frequency[2]. The exploitation of the spectrum was quite inefficient so that only relatively few consumers could have a telecommunication conversation at the same time in a given geographical area. As a result, economies of scale in production and network operation could not be fully exploited and the industry was regulated much like a natural monopoly in most countries, with the notable exception of Sweden, France and Finland. The second generation analogue systems, introduced during the second half of the 1980s, used a portion of the spectrum around the 900 MHz frequency. The higher frequency implies the need for setting up more base stations, but the denser layout of base stations over the territory permits to better exploit the spectrum and to squeeze more users into the network. The corresponding increase in capacity thus made it technically possible to introduce more competition. However, a second license was given only in the UK.

The really fundamental improvement in the exploitation of the radio spectrum occurred with the transition from the analogue to the digital technology. Digital technology was introduced in the same 900 MHz spectrum as analogue technology. Digital technology, however, uses the spectrum much more efficiently and is able to accommodate three to four times more customers (Garg and Wilkes, 1996). The most widely used first generation digital system is the European standard GSM 900 (Global System for Mobiles), though there are competing standards world-wide such as CDMA and D-AMPS. Second generation digital systems work at the 1800 MHz frequency, for example DCS 1800 which is also known as GSM 1800 because it uses the same standard as GSM 900 and the systems are compatible using "dual" handsets. These 1800 MHz systems can accommodate even more customers.

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[1] ITU (1995) estimates the investment cost of a digital fixed line at US $2 000. The average investment cost for a new digital mobile subscriber is less than half of this and moreover falling rapidly.

[2] MHz is the acronym for Mega-Hertz, i.e. waves with a frequency of 1 million per second.

2.2. *Regulatory developments*

Mobile telecommunications is a regulated industry, though it was the first major sector which in most countries was opened up to some form of competition by allowing entry of firms. Entry however is regulated because of the scarcity of the spectrum. This implies the need for a licensing policy by the government, appropriately taking into account the existing technological limits. Several important decisions are taken by governments: the technological standard to be adopted (if any), the number of licenses to be granted and the procedure by which licenses are granted. Thus the diffusion of mobile telecommunications is likely to be related to the policies adopted.

Standards

The national policies during the analogue period resulted in the coexistence of different, incompatible standards. Some countries, such as the U.K., did not specify a standard when granting licenses for the use of the spectrum (Valletti and Cave, 1998), whereas other countries, such as Germany, UK and the Scandinavian countries, specified a standard, sometimes in the context of industrial policies of promoting the domestic industry.

Table 1 shows the different analogue standards adopted in the E.U. countries. The different standards listed are not compatible, which has implications for both producers of equipment and consumers. For producers, economies of scale in the production of equipment are not fully exploited because national markets are too small. For consumers, “roaming” is not possible, i.e. the practice of bringing the handset in another country with a different standard for making and receiving calls. The most widespread analogue standard in Europe is the NMT standard. It was adopted first by the Scandinavian countries in the early 1980s[3]. Later the standard was also adopted in other Western European countries and in all of the Central and Eastern European countries.

With the introduction of the digital technology, a single European-wide standard was achieved and the European Commission took care of diffusing it. The Directive in 1991 (Directive 91/287) instructed the E.U. member states to adopt the GSM standard. This co-ordinated approach has often been used as an example of a successful common European industrial policy. It has been claimed that the GSM standard has been responsible for generating important economies of scale in manufacturing and network operation. Moreover, widest possible roaming through compatible networks could be used as an important marketing asset.

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[3] For a detailed description of the evolution of the NMT standard see Mölleryd (1997). The standard was forcefully promoted by the Swedish telecommunications operator, against the ambitions of the most important national equipment manufacturer Ericson, which favoured the adoption of the US or UK standards to exploit economies of scale in the production of equipment (p.26). One of the reasons of the pervasiveness of NMT was that it allowed roaming in Scandinavia.

Number of licenses

During the period of the first and the second generation of analogue mobile telecommunications, countries largely followed uncoordinated licensing policies. Most countries granted a single monopoly license for the first generation analogue period (450 MHz). This almost always went to the same firm that had already the monopoly for fixed line telecommunications services. Exceptions were France, the U.K. and Sweden, where a duopoly for mobile telecommunications services was established. The common justification for the restricted number of licenses during this period was the limited capacity to offer spectrum to users and the resulting problem that economies of scale would not be fully exhausted as the construction of a mobile telecommunications network requires huge up-front investments.

As demand for mobile telecommunications services was raising, pressure to grant additional licenses for mobile communication services increased. Several countries which had already granted a 450 MHz license, took advantage of the second generation analogue technology to grant additional licenses in the 900 MHz band of the spectrum. However, in most cases the licences went to the operator that had already a 450 MHz license.

With the introduction of the digital GSM technology, the European Commission started to actively promote a co-ordinated approach with more competition. A Green Paper on the sector set out the EU's policy orientations.[4] The EU Directive 96/2 formally instructed the member countries to grant at least two licenses for GSM 900 services and allow further firms to enter DCS 1800. In fact, in each E.U. country there are nowadays at least two operators for digital mobile telecommunications services.

Table 2 shows the first adoption dates of mobile telecommunications technologies in the E.U. The total number of licenses that were eventually granted for a certain generation is given by the number of dates for each technology. The table shows that the timing of licenses varied considerably across countries, even during the digital technology area when countries were obliged to follow the E.U. Directive. The first countries to adopt GSM did so in 1992, whereas the last one, Spain, adopted in 1995. Notice also that Greece did not have mobile telecommunications services at all until 1995, when it gave two GSM licenses. As will be discussed later, heterogeneity in the timing of licensing has implications for the diffusion path of technologies[5].

[4] Towards the Personal Communications Environment : Green Paper on a common approach to mobile and personal communications in the European Union : COM(94) 145 final, 27.04.1994

[5] Regulatory delays in the introduction of new products such as mobile telecommunications services can be very costly. Hausman (1997) estimated that the delay in licensing mobile telecommunications in the US led to welfare losses for US consumers in the range of $31-50 billion a year,

Licensing procedures

Governments have followed quite diverse approaches in allocating spectrum licences. The first spectrum licenses for mobile telecommunications services during both the analogue and the digital period were granted automatically to the incumbent firm already supplying the fixed line services, which in most cases was at that time a state owned monopoly. Second licenses were usually granted through an administrative procedure, a "beauty contest" by which various candidates were compared on the basis of several criteria. This approach enabled the governments to follow a discretionary policy, and take into account policy objectives that may have been more difficult to achieve otherwise.

This duopolistic market structure can have several features. An important distinction is whether the duopoly has simultaneous entry or sequential entry. In the EU the majority of the countries, i.e. 9 out of 15, adopted a sequential entry approach[6]. In most of the sequential entry cases the digital license was granted first to the holder of an analogue license.

With GSM licenses several countries have started an auction process, as previous procedures have been criticised for providing winners with windfall profits and creating distortions in the allocation of scarce resources. In principle, the auctioning process should ensure that the spectrum would be allocated to the firm that values the spectrum most and therefore would use it as fast as possible for the best as possible application (see McMillan, 1994; Cramton, 1995). This has led to escalating licence fees that had to be paid for GSM licences[7]. The bid for the second GSM licence led to the policy issue whether a first GSM operator would have to match it with an equal payment. Whereas some national governments were reluctant to impose such a payment on the first operator, the European Commission insisted on equal treatment of the two operators, either through an equal licence fee or other compensations.

The lack of a common and fast procedure to grant licenses, and the sometimes involved local political discussions, implied a quite high dispersion in the adoption dates across countries, as is evidenced by Table 2. The Scandinavian countries played a leading role in granting licenses for the analogue technology, with first licenses as early as 1981 in Sweden. For the first digital technology licenses, the international differences in adoption dates have been smaller, much due to the co-ordinating efforts of the European Commission. However, the differences in the adoption dates for the second digital licenses again varied significantly across countries, despite the European Directive.

[6] The simultaneous approach is understood as both firms starting services within three month from each other. The countries that adopted a simultaneous approach for GSM were Denmark, Finland, Germany, Greece, Portugal and Sweden. Sweden was the only country that gave three licenses for GSM 900.

[7] Incidentally, the highest license fees, in terms of fees per head, were paid in Austria and Belgium, with $50 and $30 respectively. These countries used a mixture of the administrative tender procedure with sealed bid auction aspects. See Girard and Gruber (1996) for details.

2.3. Understanding the diffusion of mobile communications services

Both the technological developments in mobile telecommunications and the role played by the governments in issuing licenses may have affected the diffusion pattern of mobile telecommunications. Technological innovation permitted to increase the capacity of the radio spectrum, especially since the introduction of the digital technology. Under such conditions, even a monopolist may find it profitable to reduce prices to attract new subscribers. The diffusion may have been further influenced by the adoption of a common European standard associated with the digital technology, increasing possibilities for economies of scale in the supply of equipment and consumer roaming. In sum, the technological changes that led to an increase in capacity and service quality may explain *global* increases in the number of subscribers, common to all countries. In contrast, the decisions taken by the local governments, regarding the timing and the number of the licenses granted, may explain why in some countries the diffusion occurred more rapidly than in other countries. During both the analogue and the digital area, there have been periods of monopoly and periods of (duopoly) competition, and competition was not introduced at the same time in all countries. Furthermore, during the early years, there were even countries without any supplier.

A central question is whether the diffusion of mobile services has been largely determined by the technology-driven capacity constraints and standardization, or whether, in addition, the timing of first licenses and the introduction of competition has played a significant role. These questions are addressed in the next sections based on an econometric model of technology diffusion. The robustness of the results are investigated by also considering alternative determinants that may have been important in the diffusion of mobile services, in particular the size of the existing fixed line network, and GDP per capita.

3. The econometric model of diffusion

Like all innovations, mobile telecommunications are not immediately adopted by all potential subscribers. The adoption decision takes time. Various alternative diffusion models have been used to describe this process. Griliches (1957) proposed an “epidemic” diffusion model to study the diffusion of hybrid corn.[8] In this model (as in other diffusion models) the flow of new adopters of the technology is related to the stock of existing adopters. When the stock of existing adopters is small, there is little risk of “contagion”. As the stock increases, the risk of contagion increases, implying an exponential rise in the flow of new adopters. As the stock comes closer to the total number of potential adopters, the flow of new adopters gradually decreases and eventually becomes zero. The diffusion of the new technology thus follows an S-shaped function.

[8] Chow (1967) applied such a model to study the diffusion of computers. An alternative model has been proposed by Bass (1969). For a survey, see Davies (1979) and Stoneman (1983).

More specifically, 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 epidemic diffusion model follows the standard logistic function:

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

Three important elements determine the shape of this function: the total number of *potential* adopters, the *timing* of initial adoption, and the *speed* of adoption. First, the total number of potential adopters, y_{it}^*, may be known or estimated, for example as a constant fraction of the total population. Second, the variable a_{it} in (1) is a location or “timing” variable. This shifts the S-shaped diffusion function upwards or downwards, without affecting the S-shape otherwise.

Finally, the variable b_{it} is a measure of the diffusion speed. This can be verified from differentiating (1) with respect to t:

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

which implies that b_{it} equals the growth rate in the number of adopters, relative to the proportion of agents who have not yet adopted the innovation. The second derivative of (1) is positive for $y_{it} < y_{it}^*/2$, and negative if the reverse holds. The diffusion of the number adopters thus follows an S-shaped pattern, with a maximum speed reached when half of the total number of potential adopters has effectively adopted the new technology.

These three elements – total market potential, timing and speed of adoption – provide sufficient flexibility to address the questions on the diffusion of mobile communication services posed in the previous section.

Econometric specification

The total number of potential adopters, y_{it}^*, is assumed to evolve proportionally to the total population, POP_{it}. Hence, we specify:

$$y_{it}^* = \gamma\, POP_{it},$$

where γ is the proportion of the population that eventually will adopt a mobile. In principle, it would be possible to allow economic determinants, such as income, to influence the total market potential, or to allow the fraction of the total population to be country specific (by introducing fixed effects γ_i). In practice, the parameter γ proved difficult to estimate, related to the fact that our sample does not cover a sufficiently long time period to also include the mature stages of diffusion. Since understanding the market potential is not our main focus, we decided to keep the specification simple in this respect.

The location variable a_{it} is specified as:

$$a_{it} = \alpha_i^F + \alpha^D \, DIG_{it}, \tag{2}$$

where DIG_{it} is a dummy variable equal to one if country i has already introduced the digital technology at time t, and 0 otherwise. The α_i^F are fixed effects for each country i, and capture an adoption lag (or lead) relative to a base country. The parameter α^D captures the instantaneous effect of the introduction of the digital technology. Below, we formulate hypotheses about possible restrictions that may hold for α_i^F and α^D.

The speed of diffusion is specified as:

$$b_{it} = \beta_i^F + \beta^D \, DIG_{it} + \beta^{CA} \, CMPA_{it} + \beta^{CD} \, CMPD_{it} + z_{it}\beta, \tag{3}$$

where β_i^F are fixed effects reflecting the autonomous diffusion speed, allowed to be country-specific, and β^D captures the effect of the presence of the digital technology on the speed of diffusion. Two competition dummy variables are also included, $CMPA_{it}$ and $CMPD_{it}$, which equal one if there are at least two competitors for the analogue and digital technology, respectively. The vector z_{it} refers to standard demand variables, in particular income and the presence of substitutes or complements for mobile telecommunications services. Income is measured by gross domestic product per capita, GDP_{it}. The number of mainlines per capita in country i at time t, $MNLINE_{it}$, captures the size of the fixed network and may have a positive or a negative effect, depending on whether adopters view mobile communications services as a complement or a substitute for a fixed connection. For the other “standard” demand variable, price, we have no data at our disposal for all periods and countries. A good measure for price is complicated by the complex structure of mobile tariffs.[9] The variable DIG_{it}, partly referring to the capacity increase during the digital technology, and $CMPA_{it}$ and

[9] The price to be paid for adopting mobile telecommunications services includes an initial connection fee, a monthly rental charge and a tariff per minute of usage. Furthermore, a whole menu of different tariff structures is usually offered to consumers.

$CMPD_{it}$, capturing the presence of a second competitor, may be viewed as proxies or underlying determinants of the price variable.

Testable restrictions

The variables $CMPA_{it}$, $CMPD_{it}$, and z_{it} only enter in b_{it}, and not in a_{it}. In contrast, the digital technology variable DIG_{it} and on the country-specific fixed effects are allowed to enter both terms unrestrictedly. It is however possible that these variables have closely related effects. We have therefore tested several possible restrictions that may apply to (2) and (3).

First, consider the effect of the introduction of the digital technology, DIG_{it}. Let T_i^D be the time at which the digital technology has been introduced in country i. A testable restriction is whether, at time T_i^D, there is merely an increase in the speed of diffusion ($\beta^D>0$) or whether, in addition, a discontinuous upward jump took place. It is straightforward to verify that the absence of a discontinuous upward jump at T_i^D implies:

Restriction 1. $\alpha^D + \beta^D T_i^D = 0$,

whereas an upward jump implies the expression is positive.

Second, consider the country-specific fixed effects. Recall that the α_i^F capture the time lag (or lead) relative to a base country, whereas the β_i^F capture the differences in the autonomous diffusion speed relative to that base country. An interesting hypothesis is whether a country that adopts relatively late also experiences a faster rate of diffusion. This may be the case for several reasons, such as declining cost of investment through calendar time, international learning, etc... To the extent that this is indeed the case, one may speak of international convergence, or catching-up by the late-comers. A simple way to incorporate convergence, is through the following restriction:

Restriction 2. $\beta_i^F = - \lambda\alpha_i^F$

against the alternative hypothesis that the fixed effects are unrestricted. To interpret Restriction 2, one can verify that any country i and j would converge to the same number of adopters (holding all variables constant except for the time lag of adoption and diffusion speed) at time $t = 1/\lambda$. Hence, the inverse of the parameter λ may be interpreted as the time at which countries converge. Although this restriction may be overly restrictive (since countries presumably do not converge at the same time, if they converge at all), it does capture convergence in a parsimonious way.

Data description

The study is based on annual data and covers all 15 member states of the EU. The data on the number of subscribers at the end of each year and time of introduction of mobile telecommunications technologies is from the trade press, in particular from *Mobile Communications* for the period 1992-1997 and from International telecommunications Union (World Telecommunications Indicators) for the period 1984-1991. The data are broken down by technology for each country. Data on GDP/head is from the OECD. Data on the number of fixed mainlines are from the International Telecommunications Union (World Telecommunications Indicators).

4. Empirical Results

The diffusion model is estimated using non-linear least squares, after adding an error term to (1). In a first table of estimates, Table 3, we present the results of regressions in which GDP_{it} and $MNLINE_{it}$ are excluded. Problems of convergence of parameter estimates occurred in some cases when both these variables and the country-specific effects were included. The difficulties disappear if one fixes the parameter γ to a known value. Therefore, in a second table of estimates, Table 4, we present results with GDP_{it} and $MNLINE_{it}$ included, and with γ fixed in those cases where parameter convergence could not otherwise be obtained.

Before considering the estimates, notice that it was not possible to reject Restriction 1, implying that the introduction of the digital technology did not imply a discontinuous jump in the number of adopters. The t-values for this hypothesis were 0.66 and 0.30, when GDP_{it} and $MNLINE_{it}$ are excluded and included, respectively. We therefore only present the results with Restriction 1 imposed. This did not affect any of the parameter estimates and reduced some of the standard errors.

Table 3 and Table 4 each present three different regressions. In the first regression, the country-specific fixed effects for the diffusion speed (β_i^F) are restricted to zero. In the second regression they are included. In the third regression they are restricted according to Restriction 2. Quasi-likelihood ratio test statistics showed that both the first and the third regression model may be rejected against the second (unrestricted) model, and the first model may be rejected against the third. Yet, the results of the restricted regressions are also presented since they provide some interesting further insights.

First consider the estimates in Table 3. The first regression, which restricts the countries to have the same autonomous diffusion speed, i.e. $\beta_i^F=\beta^F$, is informative in that it obtains a quite precise estimate of the total market potential, in contrast to the second and the third regressions. The estimated fraction of the population that is a potential buyer for mobile communications services is 0.62, with a small standard error of 0.05. This estimate of a penetration rate of 62 mobile subscribers per 100 inhabitants is not unrealistic, though slightly higher than industry forecasts[10]. The reason why such a precise estimate could be obtained in the restricted regression, is essentially the pooling of the countries: some countries are still at the early stages of the diffusion, whereas other (mainly Scandinavian) countries, have reached phases closer to maturity. The pooling thus offers a fairly complete picture of the S-shaped diffusion curve. When countries are allowed to grow at different speeds, as in the second and the third regression, the estimates of the total market potential are essentially uninformative.

For the discussion of the main parameters of interest in Table 3, we concentrate on the second regression, which allows for country-specific diffusion speeds and is our statistically preferred specification. The diffusion speed parameters, β_i^F, has an estimated value (averaged over all countries) of about 0.30, implying a maximum "autonomous" growth rate of about 15 percent at the inflection point when half of the potential consumers have adopted. The coefficient for the variable DIG_{it} measures the role of the transition from analogue to digital technology and the introduction of competition in speeding up the diffusion of mobile services. The estimates show that the technology effect is relatively large, with an estimate of 0.13. Combined with the result that Restriction 1 could not be rejected, one may describe the transition form the analogue to the digital technology as smoothly though sharply accelerating the diffusion of mobile communications. The transition implied a drastic increase in spectrum capacity, apparently inducing even monopolists to cut prices to attract a larger amount of adopters. Even independent of increased capacity, the digital technology may have stimulated the diffusion, because of the advantages (e.g. roaming) associated with common GSM standard.

The effect of introducing a second competitor, measured by the coefficients of the variables $CMPA_{it}$ and $CMPD_{it}$, is also significant. The magnitude of this effect is, however, much smaller than the technology effect. Note that the introduction of a second competitor has been of greater importance during the analogue than during the digital period (estimates of 0.023 and 0.014, respectively). This is possibly due to the considerably higher prices during the analogue period. Moreover, in many countries analogue mobile telecommunications services were supplied by a monopoly with an prolonged exclusive licence. With digital services

[10] Salomon Brothers (1997), in a well documented study by investment bankers on mobile telecommunications, expect a penetration rate of 32 subscribers per 100 inhabitants in Western Europe by 2005. However the authors point out that this is a conservative estimate, conceding that penetration rates in the range of 50 to 80 are not unrealistic. Moreover, market forecasts in the industry have consistently underestimated the actual penetration rate. Finally, note that Finland had reached a penetration rate of almost 50% by September 1998.

instead, it was known at the outset (from the EU Directive) that any monopoly, if at all, would be granted only over a very limited period.

To check for the robustness of our estimates, we experimented with alternative definitions of the competition variable. To incorporate possible preemptive behaviour, we specified the competition variable to equal one from the year preceding actual competition. We also considered a specification allowing for a different effect when competition was introduced simultaneously rather than sequentially. We finally estimated a regression with a separate dummy variable for duopoly and triopoly market structures. None of these specifications altered our conclusion of a significant, though relatively moderate competition effect as compared to the technology effect. The results point out that the technological changes appear to have been dominant during the studied period, and that the effects of introducing competition should at present not be exaggerated.

This is consistent with the findings in Parker and Röller (1997), who focus on competition in more detail, but abstract from dynamic aspects such technological developments. They study various aspects of competition in the U.S. mobile telecommunications market, such as the degree of collusion, cross-ownership and multimarket contact. They find that the duopoly structure of regional markets leads to a level of collusion that is significantly higher than under a noncooperative Cournot duopoly, and significantly though not substantially smaller than under the monopoly outcome.[11]

A final insight from the second regression in Table 3 arises from plotting the country-specific location effects α_i^F against the country-specific diffusion effects β_i^F. This is done in Figure 1. This graph reveals the following striking finding: there is a remarkably neat, linear relationship between the timing of adoption and the subsequent speed of adoption. Countries that adopt at a later date on calendar time also experience a faster growth. One may thus speak of a catching-up effect of late-coming countries. This finding may be attributed to several factors. First, the cost of infrastructure investment is decreasing over calendar time, giving late coming countries a relative advantage and enabling them to adopt faster thanks to lower adoption costs. Also the cost of subscriber equipment, mainly the handset, is declining thanks to the falling price of electronic equipment. Second, using the frequent interpretation of the diffusion speed parameter as a sort of "learning" parameter, the catching up effect may be attributed to international learning spillovers. Finally, quality of mobile telecommunications services is increasing: with GSM wide-ranging international roaming is possible and consumers have a larger incentive to adopt, since they benefit more from international network externalities.

[11] These statements can be verified from Parker and Röller estimated "conjectural variation" parameter θ=.857, with a reported t-statistic of 20.3.

Given the strong negative and linear relationship between the location and diffusion speed fixed effects, it is natural to consider a more restricted regression, imposing this relationship. This is what restriction 2 does. The results are presented in the third regression of Table 3. As could be expected from Figure 1, the parameter λ is very precisely estimated. This implies that the first regression, which implicitly sets λ=0, is rejected by the data. (The fully unrestricted regression remains statistically superior, though only marginally so.) The inverse of λ is approximately 22. Since our data set starts in 1984 (time t=0 at the year 1984) this estimate implies that international convergence in the total number of adopters will be reached around the year 1984+22=2006.[12] Our results thus show that countries which issued spectrum licenses rather lately, due to whatever local political reasons, eventually catch up. Nevertheless, some may view the delay as quite substantial, for example in light of the large welfare losses from delayed adoption as reported by Hausman (1997) for the U.S., see footnote 5.

Now consider Table 4, presenting the results when GDP_{it} and $MNLINE_{it}$ are included. Most parameter estimates are robust with respect to the inclusion of these variables, with the exception of the autonomous diffusion parameter which increases considerably in size (from 0.30 to 0.60 in the first specification). In the first, restricted specification, the parameter estimate of $MNLINE_{it}$ is significantly negative, indicating that consumers perceive mobile communications services as a substitute for the fixed network. Mobile telecommunications were conceived in the early years as a complementary service to fixed telecommunications, mainly for business people and wealthy persons, designed to give the additional feature mobility. However, as mobile telecommunications become a widely spread of service and tariffs comparable fixed telecommunications, substitution effects may become predominant.

The parameter estimate of GDP_{it} is positive, although not significant. In the second, unrestricted specification, the signs of the two parameters remain the same, though the significance is reversed. This illustrates the high degree of multicollinearity between the two variables, known also as the Jipp-curve (Jipp, 1963). Previous studies for a large set of countries typically indicate correlation coefficients of around 0.90 between GDP/head and mainlines/head (Saunders et al., 1994, chapter 4), as is also the case in the present data set. The third, partly restricted specification, which imposes convergence, further establishes the robustness of the results. In sum, the results from Table 4 indicate that there is some substitution between mobile and fixed communications services and some positive income effect, though the effects could not be estimated very precisely due to multicollinearity. The other parameter estimates confirm our earlier conclusion, i.e. that the diffusion of mobile

[12] Recall that this projection is based on our restricted specification, implying convergence at the same point in time. The restricted convergence specification also has the unappealing property that countries would start to diverge again after the point where convergence has been reached. These considerations would become relevant, once the data are updated to cover a larger time horizon, closer to the year 2006.

communication services has been driven to an important extent by the capacity increases following the transition from the analogue to the digital technology.

5. Conclusions

This paper studied the determinants of the diffusion of mobile telecommunications services in the European Union in a logistic model of technology diffusion. Our empirical results indicate that some 60% of the total population will eventually adopt mobile telecommunications. We find that the transition during the early nineties from the analogue to the digital technology, and the corresponding increase in capacity, has had a major impact on the diffusion of mobile telecommunications. Apparently, the technological developments induced even monopolist operators to reduce their prices and attract more adopters. Nevertheless, the impact of introducing competition was also significant, though the effect was proportionately smaller. Competition played a more prominent role during the analogue period, which is possibly due to the considerably higher prices during the analogue period. No evidence of preemptive behaviour by incumbents could be found. Finally, countries which granted licenses at a later point in time show a significant catching-up, though international convergence may be expected only by the year 2006. The results remain robust when other determinants of diffusion are included. The fixed network seems to be perceived as a substitute for the mobile network, and GDP per capita seems to have a positive effect. The role of these effects, however, has to be interpreted with some caution because of multicollinearity problems.

The results involve a wide range of policy issues – including the role of technology, the timing of first licenses, and the introduction of competition. The importance of improvements in technology appears clear and hard to underestimate. The role of the timing of first licenses demonstrates that early countries have a fairly long persisting lead (until the year 2006). As indicated by other studies, the welfare costs associated with such a persistent delay may be quite high. Finally, the relatively small estimated effect of competition is consistent with evidence for the U.S., but should be put in perspective. First, the sample covered mainly movements to duopoly. The effects of even more competition remain to be seen as further licenses are being issued. Second, even if competition has a relatively small effect on the adoption decision by consumers, this does not imply similar effects on the usage decision.

These qualifying statements call for various interesting directions in future work. For example, detailed price data (which is not an obvious task) may be collected to achieve further results on the differences between monopoly behaviour and competition. The role of the local policies followed in the various countries may be studied in further detail to obtain additional insights on the differences in adoption levels and speeds across countries. Finally, the evolution during the next 10 years, when the industry will have reached a stage closer to maturity, will yield interesting new data against which the results of this paper can be confronted.

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Table 1. Analogue mobile telecommunications technology standards adopted in the EU countries

	Analogue 450 MHz	Analogue 900 MHz
Austria	NMT	TACS
Belgium	NMT	-
Denmark	NMT	NMT
Finland	NMT	NMT
France	RC2000/NMT	-
Germany	C-450	-
Greece	-	-
Ireland	-	TACS
Italy	RTMS	TACS
Luxembourg	NMT	-
Netherlands	NMT	NMT
Portugal	C-450	-
Spain	NMT	TACS
Sweden	NMT	NMT
United Kingdom	TACS	TACS

Source: Mobile Communications.

Legenda

TACS: Total Access Communications System (UK standard)

NMT: Nordisk Mobil Telefon (Scandinavian standard)

C-450: C-Netz (German Standard)

Table 2. First adoption dates of mobile telecommunications technologies in the EU

	Analogue 450 MHz	Analogue 900 MHz	Digital 900 MHz (GSM 900)	Digital 1800 MHz (DCS 1800)
Austria	Nov-84	Jul-90	Dec-93;Oct-96	during 98
Belgium	Apr-87		Jan-94;Aug-96	during 99
Denmark	Jan-82	Dec-86	Jul-92; Jul-92	Aug-97
Finland	Mar-82	Dec-86	Jul-92; Jul-92	Mar-98
France	Nov-85;Aug-89		Jul-92;Dec-92	May-96
Germany	Sep-85		Jun-92;Jul-92	May-94;Oct-98
Greece			Jul-93;Jul-93	Jan-98
Ireland		Dec-85	Mar-93;Jul-93	during 99
Italy	Sep-85	Apr-90	Oct-92;Oct.95	during 98
Luxembourg	Jun-95		Jul-93;Apr-98	
Netherlands	Jan-85	Jan-89	Jul-94;Oct-95	during 99
Portugal	Jan-89		Oct-92;Oct-92	during 98
Spain	Jun-82	Apr-90	Jul-95;Oct-95	during 98
Sweden	Aug-81;Dec-82	Dec-86	Sep-92;Sep-92;Nov-92	Jan-98
United Kingdom		Jan-85;Jan-85	Jul-92;Jan-94	Sep-93;Apr-94

N.B. The number of dates indicates the number of licences.

Source: ITU and Mobile Communications.

Table 3. Results for diffusion equation (1), GDP and MNLINE excluded

	restricted	unrestricted	partly restricted
fraction of population, γ	0.623* (0.048)	1.394* (0.441)	1.198* (0.405)
location fixed effects, α_i^F	YES	YES	YES
diffusion speed parameters			
fixed effects, β_i^F	NO	YES	NO
autonomous diffusion speed, β^F	0.264 * (0.029)	0.295* (0.067) [a]	0.381* (0.037)
convergence parameter, λ			0.046 * (0.005)
digital technology, β^D	0.289* (0.041)	0.130* (0.033)	0.162* (0.042)
analogue competition, β^{CA}	0.040* (0.013)	0.023* (0.010)	0.025* (0.013)
digital competition, β^{CD}	0.016* (0.007)	0.014* (0.005)	0.011* (0.006)

[a] Fixed effects β_i^F, averaged over all countries. Country-specific fixed effects plotted in Figure 1.

Standard errors are in parentheses. A star indicates the coefficient is significant at 95% confidence level.

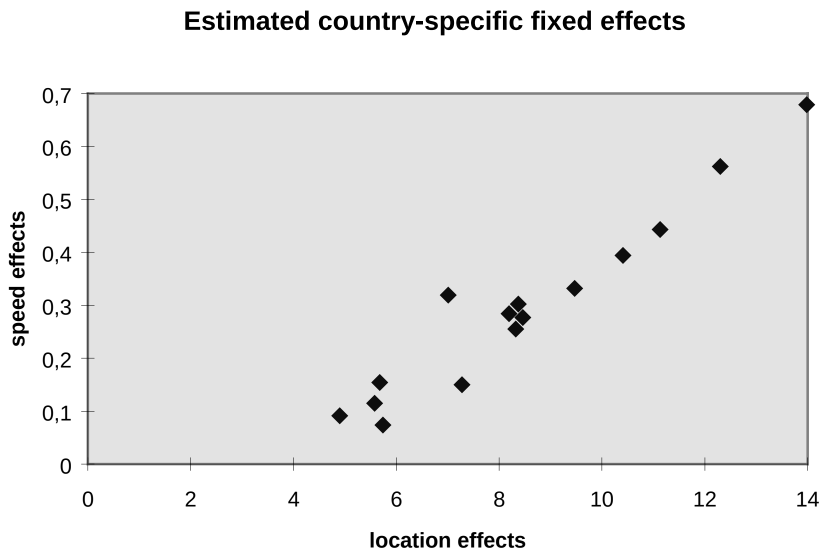
Table 4. Results for diffusion equation (1), GDP and MNLINE included

	restricted	unrestricted	partly restricted
fraction of population, γ	0.686* (0.057)	0.69	2.002 (1.179)
location fixed effects, α_i^F	YES	YES	YES
diffusion speed parameters			
fixed effects, β_i^F	NO	YES	NO
autonomous diffusion speed, β^F	0.630* (0.078)	0.144* (0.088) *	0.631* (0.051)
convergence parameter, λ			0.043* (0.004)
digital technology, β^D	0.295* (0.037)	0.136 * (0.04)	0.106* (0.041)
analogue competition, β^{CA}	0.040* (0.012)	0.019 (0.011)	0.020* (0.011)
digital competition, β^{CD}	0.015* (0.006)	0.017* (0.006)	0.008 (0.005)
GDP_{it}	0.905 (1.425)	1.533* (0.376)	0.942 (0.749)
$MNLINE_{it}$	-0.615* (0.115)	-0.114 (0.210)	-0.334* (0.070)

[a] Fixed effects β_i^F, averaged over all countries.

Standard errors are in parentheses. A star indicates the coefficient is significant at 95% confidence level.

Figure 1



location effects: α_i^F (in absolute value)

speed effects: β_i^F