Handicapping Countries in the Race to Digital Switching

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Abstract

This paper examines the diffusion of digital switching in 19 countries by specifying a model of technology choice and testing the significance of the implied determinants of adoption. The results are compared and contrasted with previous analyses of the adoption of digital switching within the U.S. In particular, the results suggest that previous analyses of the effects of telecommunications infrastructure on GDP, such as Roller and Waverman (2001), may achieve greater statistical power by accounting for the type of infrastructure as well as the level of infrastructure.

1 Introduction

As telecommunications services have grown more important, a variety of studies have tried to quantify the relationship between telecommunications infrastructure and economic growth (see Roller and Waverman 2001, Lichtenberg 1995, Roller and Waverman 1996, Norton 1992, and Hardy 1980). This literature is subject to the usual problems in identifying causality, but the studies have invariably found a strong correlation between telecommunications infrastructure investments and economic growth. Various public entities have recognized this correlation and instituted programs to promote the deployment of telecommunications technologies. For example, the World Bank's Information Development Programme disseminates policy advice on information and communication technologies for development and best practices. The International Telecommunications Union has established telecommunications training centers worldwide. The United Nations' Economic and Social Council created the ICT Task Force and Trust Fund to assist in deploying information and communication technologies. Also, the G8 states created the Digital Opportunities Task Force to match donors with projects promoting telecommunications technologies for development. (Campbell 2001)

All of these efforts require an understanding of how and why telecommunications technologies are adopted. If a policy maker wishes to speed up adoption of a technology, it must identify the bottlenecks that are constraining adoption. Furthermore, study of how firms adopt new technologies helps policy makers determine whether intervention is worthwhile. If a country has efficient capital markets, then the factors constraining adoption should provide insight both into how to speed adoption and whether intervention is justified.

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This paper examines the diffusion of one of the most important telecommunications innovations in recent decades – the digital switch. Section 2 discusses the history of telecommunications switching and places the diffusion process in context by discussing the relative merits of analog and digital switches. Section 3 provides an overview of the regulatory structures in the countries studied. Section 4 examines the nature of the adoption decision with respect to switches and discusses the implied determinants of adoption. Section 5 describes the two data sets used: historical data for 19 developed countries from 1975 to 1998, and more detailed data from the United States from 1983 through 1996. Section 6 presents empirical results on the determinants of adoption. Section 7 summarizes the findings and outlines areas for future research.

2 History of telecommunications switching

A telecommunications switch is a device that routes a signal between two points (such as two telephones). The oldest switches were human operated switchboards where an operator would ask for whom the call was intended and complete the circuit by hand. In most industrialized countries, however, the oldest remaining switches currently in service are electromechanical. These switches are automated versions of the human operated switchboard where circuits are physically closed without human intervention. Three classes of these switches, varying in sophistication, were available by the late 1930s. Unfortunately, in most countries little information is available about the adoption of electromechanical switches. Reliable data largely begin with the next generation of technology – the analog switch.

The first true analog switch, the 1-ESS, was installed in 1965. This commercial central office switch had stored program control (software) but still depended on space-division switching (meaning that circuits, or phone connections, consist of physically discrete paths). These older switches are collectively known as analog switches because of their reliance on circuits (therefore preserving the analog nature of the signal). Digital switches, by contrast, have a significant advantage in that they use time-division switching (also known as time division multiplexing) where multiple signals can share a single physical path.

Commercial digital switching began in 1970 with the installation of an E10 electronic switching system in France. Bell Laboratories announced in 1972 that it would develop the No. 4 ESS switching system to be aimed at very large capacity offices. It became “the first commercial stored program controlled digital toll switch to be placed in service in the world in January 1976” (Joel 1979). Digital switches were popular in developed countries with a high demand for telecommunications because of their more efficient use of the existing physical plant – a single line could carry many signals simultaneously. Also, analog switches required expensive conversion hardware when connected to digital transmission systems such as T-1 lines, which were becoming fairly widespread by the mid 1970s in industrialized countries. Digital switches were smaller than analog switches and required less power. They also did not require any conversion hardware for connecting to other digital systems.

Flamm (1989) estimated that replacing an electromechanical system with a digital stored program control system reduced lifetime maintenance costs by 40 to 60 percent of the switch’s initial cost, or annual savings of 6 to 7 percent of the switch’s cost, while "[t]he changeover from an analog switching matrix to a digital system in 1976 resulted in [lifetime] savings of 10 to 20 percent of initial cost," or annual savings equal to roughly 2 percent of the switch's cost.

It may sound like digital switches are uniformly better than their predecessors. This is not, in fact, the case. Flamm's estimates, for example, were developed with respect to the U.S. economy. Digital switches are not necessarily superior to analog switches for all countries or circumstances. A digital switch can serve more lines than an analog switch and can transmit multiple signals on a single line, but an analog switch may be more cost effective in areas of low demand (either because of low population density or low demand for telecommunications services), particularly if there is relatively little need to interface with other digital transmission facilities such as T-1s. Similarly, if a population has little demand for advanced features such as caller ID, then the ability of a digital switch to offer these services is largely irrelevant.

Adoption of digital technology is not necessarily an either/or proposition. Older analog systems such as the 1-ESS may be upgraded or used in conjunction with digital remote terminals. Furthermore, the switches themselves are not static entities. Over time, software has represented a greater proportion of the cost of a switch and existing switches may have their software upgraded repeatedly. Above and beyond the cost savings offered by digital switches, digital technology allows new services such as caller ID, voice mail and virtual call centers. Many of these services, made possible by the new generation of switches, are highly profitable in developed countries but are almost unknown in other countries. Moreover, their profitability is only known ex post. Companies and countries trying to choose their upgrade path have to predict the demand for the new services as well as simply calculating cost savings.

3 Regulation

Regulation is not a determinant of adoption in and of itself, but it can affect many aspects of the adoption decision. Regulation can affect a firm's objective function (whether it is maximizing profits or not), its costs, its revenues, and its investment options. The effects of regulation on telecommunications diffusion have been found to be important by Greenstein, McMaster and Spiller (1995), Berg and Hamilton (2001), and Gutierrez and Berg (2001). These studies also illustrate the difficulties of quantifying distinctions between regulatory regimes. That is, regulatory regimes are so varied and idiosyncratic that it is extremely difficult to quantify distinctions between them in any way except as a fixed effect.

The effects of regulation on individual aspects of the adoption decision are discussed in the appropriate sections. However, there is one overriding element to be mentioned here – the ownership of the telecommunications infrastructure. Many countries exercise direct control over their telecommunications networks through regulated monopolies. Other countries have privatized their systems, although every country has retained at least some degree of regulation. In each case the telecommunications company cares about the direct costs of deployment. However, government controlled entities may not be maximizing profits. If they are interested in maximizing consumer welfare, then they may be better able to internalize network externalities than private companies, but they may also have rather different objective functions (such as maximizing welfare for a particular voter bloc, for example). Also, a regulated monopoly will likely choose a price above the competitive level – either because of inadequate regulation or because of a conscious decision by policy-makers to use telecommunications as a revenue mechanism.

Country	Year of privatization	Share of largest operator of basic voice telephony	Year of entry liberalization	Universal access
Australia	1996-1997	82%	1991	Yes
Austria	1998	100%	1998	Yes
Belgium	1995	100%	1998	Yes
Canada	Not state owned	Unknown	1990	Yes
Denmark	1992	95%	1996	Yes
Finland	1998	55%	1993	No explicit program
France	1997	100%	1998	Yes
Greece	Unknown	100%	2001 (est.)	Yes
Ireland	1996-1997	100%	1998	Yes
Italy	1998	100%	1998	Yes
Japan	1986	64%	1986	Yes
Netherlands	1994	80%	1997	With "market failure"
Norway	Not privatized	100%	1998	Yes
Portugal	1995	100%	2000 (est.)	Yes
Spain	1997	97%	1998	Yes
Sweden	Not privatized	83%	1994	Yes
Turkey	Not privatized	100%	2006 (est.)	Yes
United Kingdom	1984	76%	1985	Yes
United States	Not state owned	62%*	1984	Yes

Table 1: Telecommunications regulation as of 1998

Note: The OECD data treat all Bell companies as a single entity.
Sources: Boylaud and Noceletti (2000); OECD Telecommunications: Regulatory Issues questionnaires.

The regulation of telecommunications in the OECD countries studied here changed dramatically during the study period. For example, most of the countries began the study period with state owned telecommunications companies, but privatized those companies, in whole or in part, during the 1990s. (Henten 2005; Boylaud and Noceletti 2000) Most of those companies also enjoyed legal or de facto monopolies on basic voice telephony during the study period. Almost every country had some form of universal service obligation, but the details varied widely. Some countries had goals such as a payphone in every village. Others aimed to provide a phone line to every household or individual that wants one. Generally, universal service programs used some combination of the following mechanisms: 1) market-based reforms (privatization and competition); 2) mandatory service obligations; 3) cross subsidies; and 4) access deficit charges (payments between operators to subsidize operations). Intven and Tetrault (2000) provide a useful overview of different universal service programs worldwide.

As a general rule, these countries were in the process of moving away from state-owned monopolies towards having multiple, competing privately-owned telecommunications providers. Almost every country in the study group had at least one substantial overhaul of its telecommunications laws and regulations during the study period. These overhauls affected every aspect of the industry, from privatization to rate regulation to universal service. While the state of regulatory flux makes it difficult to draw sharp distinctions between groups, there are a few persistent differences. Canada, Japan, the United Kingdom and the United States were all privatized relatively early or were never state owned. These countries also generally had multiple providers with substantial shares of basic voice lines, although these providers did not necessarily overlap geographically.

For countries which had historically lagged behind in telecommunications diffusion (that is, those separated by the "digital divide"), regulatory reform efforts were motivated at least in part by a desire to close the gap with countries possessing more sophisticated networks. (Campbell 2001) While these policies have their roots in the study period of this paper, they were generally not completed until the end of the study period. The possible effects of these regulatory regimes are discussed in the context of individual factors affecting the adoption decision.

4 The adoption decision

When a firm has the choice of installing a new digital switch it asks whether the net present value of installing that switch is positive. The overall level of adoption is simply the aggregate of these individual decisions. In this section I will discuss the factors that affect these adoption decisions.

4.1 Costs

The relative prices of the alternative technologies are determinants of adoption. On a cost per line basis, the relative cost effectiveness of analog and digital switches depends on the level of demand. That is, installing an analog switch is cheaper than installing a digital switch, but the digital switch can serve more customers and offer more services. Regulation and government action may also impact the costs that a firm faces. For example, some countries have implemented unbundling regulations that require incumbents to make their facilities available to competitors at regulated rates. The expected cost of such facilities is thus raised by the degree to which the regulated rates do not adequately capture the costs and risks born by the deployer. (Hausman and Sidak 1999) These unbundling requirements were implemented late in the study period for most countries.

Regulations may also affect costs through subsidies, accounting rules, or rate regulations. For example, in some countries certain types of deployment receive favorable tax status (such as broadband deployment in South Korea). In the United States the level of depreciation for existing technology was crucial under rate of return regulation. As Paul Travis explained in Telephony in 1989, the baby Bells "have billions and billions of dollars invested in the dependable and feature-rich 1A electronic analog switches, which work just fine and are not yet fully depreciated". Greenstein, McMaster and Spiller (1995) explained that such firms often have low levels of depreciation, mandated by regulators, which reduce the firms' incentives to invest in new technologies.

The physical structure of the telecommunications network may also affect costs. Portions of networks may serve primarily as transit points with few or no direct customers. Large countries with diverse population centers may have a higher proportion of these “long-haul” switches. For these countries the cost per customer of providing digital infrastructure may be higher than for smaller countries. Countries whose populations largely reside within dense population centers will also find digital switches relatively more cost effective than countries whose populations are more geographically diffuse. The size of a country and the distribution of its population are thus determinants of adoption as well.

4.2 Demand for telecommunications services

In general, firms deploy more advanced switches in areas with higher demand. For switches the relevant measure of demand is the number of lines required in a given geographic area. In part this is because digital switches are more cost effective in high density areas, and in part this is due to the demand for the more advanced services available from those switches. Dense metropolitan areas tend to contain business centers with higher demand for digital services as well. Demand is not directly observable but a variety of factors are correlated with the demand for telecommunications services. Perhaps the most direct measure is a waiting list for new services. Some countries, particularly those who do not yet have near universal telephone service available, maintain waiting lists for phone lines. The ratio of the waiting list to the number of people who do not yet have service provides an estimate of demand. However, the mere existence of the waiting list demonstrates that the country has chosen not to fully deploy its network. Since that choice was endogenous, the country may delay deploying digital technology as well. On the other hand, the country may “leapfrog” if the incremental gains are larger for it than for countries that had invested in more modern or more extensive infrastructure.[1]

The distribution of population in a firm’s area should affect the rate of adoption. However, the average population density is the wrong measure to capture this effect. Some measure of urbanization will better capture the relevant effects. In addition, the rate of growth in metropolitan areas should also affect the demand for new services and the expectations for costs over coming years. Rapidly growing urban areas would be expected to have more digital switches installed than decaying cities.

At a country level, demand is likely to be correlated with the gross domestic product. As Greenstein and Spiller (1995) have demonstrated, certain types of GDP tend to be associated with higher levels of demand, but such detailed data are not always available. GDP data may also be problematic for countries with large underground economies.

Finally, demand is affected by price. Service revenues per line provide a measure of price, but this price is not always set in a competitive market. Higher revenues per line may be indicative of greater demand, all else equal, but it is also possible that those higher revenues are due to supply being constrained below the competitive level. In that case, the effect on adoption is ambiguous – demand will be lower, but revenues per line will be higher. The lower demand may impact adoption through reduced network externalities.

[1] The international data used here do not permit an analysis of “leapfrog” behavior as they only track digital adoption. It is entirely possible, however, that some countries may choose to bypass widespread landline deployment altogether in favor of wireless technologies. (Schement and Forbes 2003; Melody 2005; Gillwald 2005). This type of divergent network development is new to the industry and is an interesting area for future research.

Also, since digital technologies need a high density of lines to be cost effective, it is plausible that countries constraining supply would adopt more slowly than countries pricing closer to the competitive level.

4.3 Network effects

Network effects impact adoption through the quality of services being offered. The value of most telecommunications services is largely a function of the number of subscribers to the service or the level of deployment of the service – this is known as a network effect, or network externality. The addition of one more subscriber or digital switch makes the service more valuable to other subscribers. Similarly, the number of existing subscribers determines the value of the service to new subscribers. Thus, the installed base of the firm (and the country) is a determinant of adoption because of its impact on demand through network externalities.

The network effects from the installed base include both technology specific and non-specific externalities. That is, a new switch provides some benefits to customers of all other switches, regardless of type. In addition, that switch may provide more benefits to customers using other switches of the same type. Adding a new digital switch will make basic services such as plain old telephone service (POTS) more valuable to all telecommunications customers simply because they can now reach more people. In addition, customers using other digital switches benefit because the digital specific services can also reach more people. For example, caller ID only functions if a particular call passes through switches that support that capability. If it passes through an analog switch that does not support caller ID, the relevant piece of data will be stripped from the signal.[2] Similarly, it is easier to integrate digital services such as T-1 lines with digital switches than with analog switches.

The impact of these externalities on adoption, however, is unclear. Rosenkranz (1997) finds that low-quality firms (using a first generation technology) have a greater incentive to adopt a third generation technology in the face of significant adoption costs than would a firm using a second generation technology. However, Farrell and Saloner (1986) point out that a large installed base with network externalities can either decrease adoption because early adopters bear a larger proportion of the transition costs, or increase adoption as users of the older technology change to prevent being “stranded”. Witt (1997) takes exception to the idea that “lock in” is significant, but concludes that a critical mass of adopters is required for a new technology to be successful. Shampine (2001) finds that, in the U.S., telecommunications companies with large installed bases of analog switches adopted digital technology more slowly than companies with a preponderance of electromechanical switches.

The ambiguous impact of network effects is largely due to the endogenous nature of the installed base. At some point in the past the firm had to decide what type of switches to install or replace. Some firms chose to install or keep electromechanical or analog switches. The most likely reasons for such a choice include low population density and/or a perceived lack of demand for new features and services.[3] Therefore, as a matter of theory,

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[2] This particular example is an over-simplification of both caller ID and the capabilities of analog switches. However, it is intended to make the point that many services are dependent upon the installed hardware and software, and that legacy hardware and software may impede their functionality.

[3] Industry participants sometimes try to explain slow adoption as a function of capital constraints. However, given efficient capital markets this explanation seems unlikely. If the perceived present value of adding new

a firm with a large installed telecommunications base but little digital technology may or may not adopt digital technology more quickly than a new entrant or country with little in the way of infrastructure. The choice of electromechanical technology over analog or analog over digital demonstrates that a firm anticipates relatively lower demand for telecommunications services in general and advanced services in particular. Similarly, a firm which adopts analog switches over electromechanical, or digital over analog, has shown that it expects a relatively high pay-off from the newer technology. Thus it is not entirely clear whether the expected gain from installing a digital switch is greater to a firm with no switch or an electromechanical switch than to a firm with an analog switch.

4.4 Firm size

Firm size has been found to be positively correlated with the rate of adoption in virtually every industry studied, albeit for a variety of reasons. For example, in an agricultural context, Feder, Just and Zilberman (1985) conclude that the high yielding crop varieties of the Green Revolution were adopted faster by larger farms. Rose and Joskow (1990) find that larger electric utilities adopt new technologies faster, and Dougherty, Germain and Druge (1995) find a similar result for the logistics management industry. Saloner and Shepard's 1995 study of ATM adoption by banks finds that the number of branches is positively correlated with the rate of adoption. They attribute this correlation to the presence of network effects. As discussed, the value of new switches rises when all switches upgrade. However, the most that any one telephone firm can do is upgrade its own switches, while the benefits from their upgrade are realized by other interconnecting firms. Hence, private incentives do not internalize all the benefits from upgrading a switch, and the size of a firm's network determines how much of the network effects it can internalize. Majumdar and Venkateraman (1998) examine the relation of switch adoption and network externalities and attribute a positive correlation between firm size and the rate of adoption of electronic switches (both analog and digital) in the telecommunications industry to network effects. See also Rogers (1995) for a discussion of the relative adoption speeds of interactive innovations.

Installing a new generation of switches also requires the development of procedures and human capital in maintaining and operating those switches. To the extent that these costs are independent of firm size, larger firms could amortize the costs over a larger base of switches. Since telecommunications firms generally make significant efforts to establish corporate-wide network maintenance procedures, it is certainly plausible that, on a per switch basis, larger firms would need to spend less on updating their internal procedures and human capital.

4.5 Fixed effects

Finally, there are a variety of firm specific effects that are difficult to capture independently. These include regulation, corporate focus and strategic plans, and complementary assets or plans. Regulation can affect adoption in many ways. For instance, it can affect the prices (and therefore the profits) that can be made from new and existing services. It can affect how and whether capital expenditures are made. It can affect the

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switches is positive, the capital should be available. In non-market economies or economies with significant corruption, then misallocation of resources becomes a more serious issue. Trade barriers can have a similar effect.

deployment and marketing of new services. Corporate focus and strategic plans reflect whether the firm is putting its money behind the services available through digital switches or whether it believes that it can obtain a greater return through some other avenue. This is tied in to complementary assets or plans. For example, a firm might be trying to establish a wireless presence and find that it is easier time to integrate its wireless operations with its analog switches. In that case the firm might delay installing digital switches in order to pursue the more immediate opportunity perceived in wireless.

5 Data

Two data sets are used to examine the determinants of adoption. A set of international data cover 19 OECD countries from 1975 to 1998. The countries included are Australia, Austria, Belgium, Canada, Denmark, Finland, France, Greece, Ireland, Italy, Japan, the Netherlands, Norway, Portugal, Spain, Sweden, Turkey, the United Kingdom and the United States. These data are drawn from the Summers and Heston 5.6 and 6.0 beta tables and the International Telecommunications Union (ITU) STARS database. Table 2 provides the names, definitions and sources of the variables used. Different countries begin reporting data in different years, and countries may begin reporting different series in different years as well. In total, the data provide 381 usable observations.

Most of the variables are straightforward. However, while the ITU tracks telecommunications investment and Summers and Heston track total capital stock, neither examines telecommunications capital. For this analysis, a telecommunications capital series is constructed following Roller and Waverman (2001), using the perpetual inventory method with a 10 percent depreciation rate and initial values set so that the telecommunications stock is the same fraction of total capital stock as telecommunications investment is to total investment for the initial year.

Total labor force is used as a proxy for overall business demand. Prices for analog and digital systems are included where they are available historically, such as in the U.S., but in general transaction price data are lacking. Similarly, the number of digital, analog and electromechanical lines is used to model the installed base where the data are available. Where these data are not available, I use the stock of telecommunications capital as a proxy for previous investments. The higher the capital stock, the larger and more sophisticated the installed base is likely to be. I also use total government expenditures as a proxy for the level of government intervention. Finally, country specific fixed effects are included to capture the effects of regulation and other elements for which data are not available.

International data set variables	
Log GE	Log of total government expenditures (billions of 1996 dollars), by country. Source: Summers and Heston.
TELP	Telecommunications services revenues divided by number of main lines (that is, revenues per line). Source: ITU.
Log GDP	Log of real GDP (billions of 1996 dollars), by country. Source: Summers and Heston.
Log TLF	Log of the total labor force of the country (millions). Source: Summers and Heston.
Log GA	Log of the geographic area of the country (thousands of square kilometers). Source: ITU.
Lag Penetration	Number of main lines per capita in the previous year, by country. Source: ITU.
WL	Per capita waiting list for lines, that is, number of people on the waiting list as a fraction of the total population, by country. Source: ITU.
Lag Log TECH	Log of the telecommunications capital stock in the previous year (log of $TECH_{t-1}$). Source: Summers and Heston.
Delta PD	Change in the percentage of digital lines, by country. Source: ITU.
Digdum	Dummy variable for the presence of digital lines, by country. Source: ITU.
United States data set variables	
DELTADIG	Change in percentage of total digital lines, by company. Source: DATAQUEST.
TOTLAG	Number of total lines in the previous year, by company. Source: DATAQUEST.
LPEM	The percentage of lines that were electromechanical in the previous year, calculated as lagged number of electromechanical lines divided by total lines, by company. Source: DATAQUEST.
METPER	Percent of population in a firm’s service area living in metropolitan areas. Source: Statistical Abstracts of the United States. Service areas are from CCMI data and company web sites. The national populations were used for Other Independents.
DELMET	The change in percentage of metropolitan population (that is, the change in METPER). Source: calculated from METPER.

Table 2: Variable Definitions

The international data are compared with results presented in Shampine (2001) which used relatively detailed data for multiple telecommunications firms in the United States. These data are compiled from various editions of the U.S. Central Office Equipment Market report (graciously provided by DataQuest) and from public sources. The data consist of holding company level information for fifteen companies (after mergers and acquisitions) on digital, analog and electromechanical lines, systems and prices from 1983 to 1996. The companies included are Alltel, Ameritech, Bell Atlantic, BellSouth, Cincinnati Bell, Frontier, GTE/Contel, Lincoln (now Aliant), NYNEX, Other Independents, Pacific Telesis, SNET, SBC, Sprint/United and U S WEST.

In the U.S. data, firm size is modeled through the number of total lines owned by the company in the previous year. The installed base is captured by the percentage of lines that were electromechanical in the previous year. The distribution of population is captured through the percent of population in a firm's service area that lives in metropolitan areas. Finally, the change in the percentage of metropolitan population is intended to capture whether urban areas are growing or decaying. Decaying areas would display less potential for revenue growth.

6 Empirical results

This section highlights several stylized facts that shed light on the adoption process, and then presents econometric analyses of the two data sets. The results for the U.S. data were developed in Shampine (2001) and are presented here for comparison with the international results.

6.1 International results

Figure 1 tracks the percentage of digital lines for each country across time. There is remarkable diversity in the initial deployment of digital technology in each country. Finland and France were the first to do substantial upgrades beginning in 1980 with the U.S. a year behind.[4] Greece got the latest start in 1990. However, this graph hides several interesting dynamics since it does not capture the relative changes in analog and digital technology. Figure 1 by itself might suggest that once countries began to deploy digital switches that they did so exclusively and never looked back since it shows a uniformly increasing proportion of digital lines. However, the story is more complicated.

Table 3 presents a snapshot of the early stages of adoption for various countries. The columns provide the percentage of new lines that are analog or digital, except where a negative figure is presented. A negative number is the percentage of the installed base being upgraded to digital – that is, if the number of new digital lines exceeds the total number of new lines in the country, the table presents the portion of existing lines that is being upgraded. These figures are approximate as the data include only the total number of lines and the number of digital lines. To put it another way, the numbers in Table 3 assume that all digital lines added in a year are de novo installations unless the total number of additional digital lines exceeds the total number of new lines.[5] Table 3 presents the period from the first adoption of digital technology until a country discontinues deploying analog technology.

Digital technology does not immediately displace analog technology for most countries. Countries continued to deploy analog lines even after digital switches were

[4] France installed the first commercial digital switch in 1970, but digital lines did not comprise a meaningful portion of its infrastructure until 1980.

[5] I also assume that all new lines are either analog or digital, not electromechanical. I am unaware of any new electromechanical switches being installed in these countries during this period.

available, and, in fact, typically deployed both digital and analog lines at the same time. Some countries (Japan and the Netherlands) made a clean break with analog, completely discontinuing any new deployment of analog technology and replacing existing analog infrastructure with digital. Most countries, however, continued to deploy both technologies for years. In the case of Turkey, the technologies have continued to be deployed simultaneously for over a decade and the country has done little to replace existing analog infrastructure.

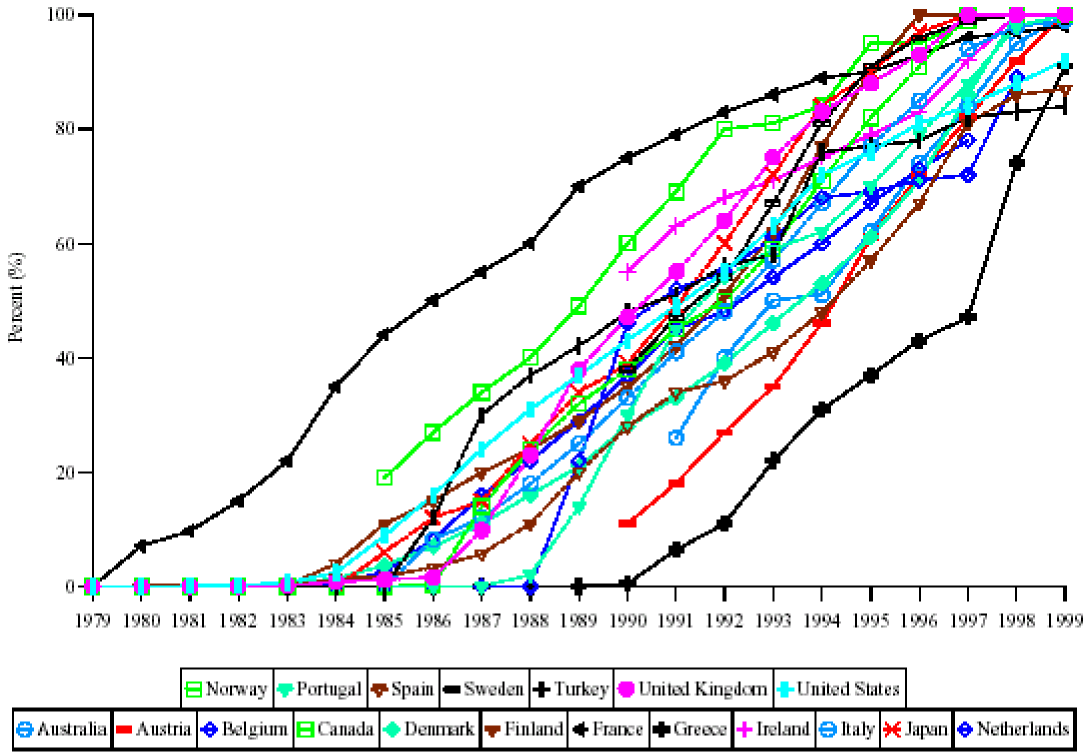

Figure 1: Percentage of lines that are digital

These data raise several questions. In particular, why do some countries begin adopting digital technology before others, and what determines the speed of the transition to digital? The first question is addressed by using a dummy for digital adoption as a dependent variable (0 if no digital adoption has occurred, 1 if some digital lines are present) and regressing various explanatory variables on it. The coefficients on the independent variables reflect their impact on the linear probability of a country adopting digital technology in a given year. Countries with a higher probability of adopting are thus likely to adopt earlier than other countries. Table 4 presents the results (excluding the coefficients on the country fixed effects).

The positive and significant coefficient on GDP indicates that wealthier countries are more likely to begin adopting digital technology than poorer countries. The coefficient on geographic area (log GA) is negative but not significant. Government expenditures are negatively correlated with the probability of digital deployment but the coefficient is not statistically significant.

Country	Year	Analog lines	Digital lines
Belgium	1982	100%	0%
	1983	97%	3%
	1984	94%	6%
	1985	35%	65%
	1986	5%	95%
	1987	-4%	100%
Denmark	1982	100%	0%
	1983	86%	14%
	1984	56%	44%
	1985	23%	77%
	1986	0%	100%
	1987	-1%	100%
Finland	1979	100%	0%
	1980	98%	2%
	1981	100%	0%
	1982	98%	2%
	1983	100%	0%
	1984	4%	96%
	1985	-3%	100%
France	1979	100%	0%
	1980	42%	58%
	1981	68%	32%
	1982	29%	71%
	1983	-1%	100%
	1984	-9%	100%
Greece	1989	100%	0%
	1990	88%	12%
	1991	0%	100%
	1992	19%	81%
	1993	-6%	100%
Italy	1985	100%	0%
	1986	-4%	100%
	1987	8%	92%
	1988	-1%	100%
Japan	1984	100%	0%
	1985	-3%	100%
Netherlands	1988	100%	0%
	1989	-19%	100%
Norway	1985	100%	0%
	1986	95%	5%
	1987	-9%	100%

Country	Year	Analog lines	Digital lines
Portugal	1987	100%	0%
	1988	81%	19%
	1989	21%	79%
	1990	-9%	100%
Spain	1983	100%	0%
	1984	73%	27%
	1985	88%	12%
	1986	65%	35%
	1987	42%	58%
	1988	18%	82%
	1989	-3%	100%
Turkey	1985	100%	0%
	1986	35%	65%
	1987	17%	83%
	1988	42%	58%
	1989	33%	67%
	1990	16%	84%
	1991	33%	67%
	1992	10%	90%
	1993	35%	65%
	1994	-14%	100%
	1995	11%	89%
	1996	4%	96%
	1997	-1%	100%
	1998	1%	99%
	1999	0%	100%
United Kingdom	1982	100%	0%
	1983	94%	6%
	1984	82%	18%
	1985	86%	14%
	1986	83%	17%
	1987	-4%	100%
United States	1980	100%	0%
	1981	99%	1%
	1982	94%	6%
	1983	82%	18%
	1984	2%	99%
	1985	-4%	100%

Table 3: New lines installed

Adj. R^2 = .6925		
Observations = 363		
Dependent Variable: Digdum		
Variable	**Parameter**	**T-Value**
Intercept	7.86	1.60
Log GDP	1.28	3.97
Log GA	-1.55	-5.45
Log GE	-0.15	-0.88
Lag Penetration	0.04	0.49
WL	-5.34	-3.33
TELP	-0.00005	-0.49
Lag Log TECH	0.44	5.17
Log TLF	-0.62	-1.30

Table 4: Linear probability of digital adoption (international)

Penetration and telecommunications capital are both measures of the installed base. Penetration reflects the ubiquity of service (lines per capita) while telecommunications capital measures the intensity of previous investment. The coefficient on lagged penetration is not statistically significant, while the coefficient on lagged telecommunications capital is positive and significant. That is, countries with large investments in extensive telecommunications systems are more likely to begin adopting digital technology than countries with less extensive networks. This result suggests that countries which historically emphasized telecommunications investment will continue to do so as new technologies become available, preserving the oft-discussed "digital divide".

The demand variables offer mixed results. It is not clear what sign should be expected for log TELP (revenue per line). Higher revenues may be indicative of higher demand, but they also may reflect constraints on supply. The coefficient here is negative, but not significant. The coefficient on the waiting list for lines is negative and significant. This variable is likely capturing the effects of previous deployment choices. Countries with large waiting lists have been slower than their counterparts in the past in deploying infrastructure. As discussed earlier, these choices are endogenous. These results suggest that countries which have been slow in the past choose to be slow with respect to digital as well. In the U.S., Shampine (2001) found that companies with large installed bases of electromechanical systems (that is, those which had not invested in analog technology) adopted digital systems more rapidly than those companies with large installed bases of analog systems. However, this effect cannot be investigated using these international data, since the data do not track electromechanical switches. Finally, the coefficient on the size of the labor force variable (log TLF) is negative but not statistically significant. These results are consistent with a persistent "digital divide". However, many countries changed their regulatory regimes near the end of the study period, at least in part because of concerns about their networks, raising the question of whether these effects persist today.

All of these results are for the probability of adopting in a given year. Table 5 presents regressions results concerning the rate of adoption. Here the dependent variable is the change in the percentage of digital lines. Again, country fixed effects are included in the specification but are not presented in the table.

Adj. R^2 = .3559		
Observations = 363		
Dependent Variable: Deltapd		
Variable	**Parameter Estimate**	**T-Value**
Intercept	0.32	0.44
Log GDP	0.13	2.69
Log GA	-0.07	-1.67
Log GE	-0.02	-0.91
Lag Penetration	-0.00	-0.26
WL	-0.76	-3.19
TELP	.00002	1.07
Lag Log TECH	0.05	3.63
Log TLF	-0.19	-2.6

Table 5: Rate of digital adoption (international)

GDP is positively associated with the rate of diffusion, just as with the probability of adoption, and is statistically significant. Some authors have suggested that higher levels of adoption are causing higher levels of GDP, but even if true this is unlikely to be a contemporary effect. It is more likely within the same year that high levels of GDP are associated with high demand for telecommunications services.

The country size and the level of government expenditures are negatively associated with the rate of adoption, although the latter is not statistically significant. At first blush, the country size result would seem to be due to lower population density, but population density is not significant when it is included as an explanatory variable. Larger countries may require more long-haul infrastructure which may be less cost effective to upgrade – that is, long-haul infrastructure does not serve customers directly, so upgrading it merely enhances the service provided by the customer's central office switch. If a country has a relatively larger proportion of long-haul infrastructure to local infrastructure, then the long-haul infrastructure provides a bottleneck for the network externalities. The country will have to upgrade the long-haul infrastructure as well as the local infrastructure to provide digital services, and that may be more expensive for large countries. Alternatively, size may be correlated with other factors that are not accounted for here.

The two measures of installed base – penetration and telecommunications capital stock – have different signs. Lagged penetration is not significant, but the lagged telecommunications capital stock has a significant coefficient. As discussed below, this result is an interesting contrast to the U.S. results.

The coefficients on the demand measures are different than in the adoption regression in Table 4. The results for the waiting list for lines variable are the same. Countries which have larger waiting lists for lines, indicating that they have been relatively slow in deploying infrastructure in the past, are also slow in deploying digital infrastructure. However, the sign on the revenue per line variable (TELP) is positive, albeit not statistically significant. The t-value of 1.07 is high enough to draw some attention, however. The higher revenues from higher prices may be outweighing the reduction in network effects from constrained supply in most countries. The theoretical ambiguity of the sign may mean that different countries are experiencing different effects, resulting in an overall lack of significance. The sign on total labor force (log TLF) is negative and significant. This result is puzzling. Most likely the size of the labor force is negatively correlated with per capita income (and thus demand), or is correlated with other excluded explanatory variables.

6.2 Comparison to U.S. results

Table 6 presents the U.S. only results from Shampine (2001). These consist of two periods because a Chow test for structural change indicated that the two periods were significantly different.[6] Company specific fixed effects were included in the specifications but are not reported here.

Variable	**1984 – 1989**	**1990 – 1996**
Adj. R^2	.1725	.3066
Intercept	-0.417 (-0.47)	-2.303 (-1.95)
TOTLAG	0.00004 (2.84)	0.000007 (1.35)
LPEM	0.137 (2.56)	0.402 (5.48)
METPER	-0.272 (-0.20)	3.018 (1.83)
DELMET	-1.353 (-0.90)	-2.298 (-2.00)

Table 6: Determinants of U.S. digital adoption

In the United States, firms with larger networks (as measured by lagged number of lines) adopted more quickly, while firms with a larger proportion of analog switches (as measured by the lagged percentage of electromechanical lines) adopted more slowly. These measures are not directly comparable to the international results, but do present interesting contrasts. In the international results, penetration, which is the variable most similar to lagged total lines, has no significant effect, while total telecommunications capital stock is positive and significantly associated with faster and earlier adoption. The difficulty in comparing the results is that, in the U.S., both larger networks and more analog switches contribute to a larger capital stock, while the two have opposite effects on adoption. As a matter of theory, however, the effect of the analog/electromechanical choice on future adoption is ambiguous. The international results suggest that, regardless of specific choices, countries which have sunk a lot of money into telecommunications infrastructure in the past are likely to upgrade their systems sooner and faster than countries which have spent less. This result is not surprising, since countries which have adopted rapidly in the past are likely to continue the policies which led to such adoption. However, many countries were privatizing their telecommunications networks during this period and opening the industry to competition, presumably in the hopes of improving telecommunications services. Isolating the effects of these policy changes on adoption is beyond the scope of this paper. However, it would be interesting to examine the post-1990s world to see how changes in privatization and competition have affected the determinants of adoption.

In the U.S. it was possible to obtain line costs by technology and company type. However, they were not significant in any specification and so were excluded. The revenue per line measure for the international data also proved to be insignificant. These results are a bit surprising. They may be due to poor measurement (for example, the revenue variable

[6] Given the regulatory changes at the international level near the end of the study period, it may be that the determinants of adoption changed for the next round of international adoption decisions (mostly wireless technologies). See, for example, Henten (2005).

may be missing some relevant services or failing to capture expected future revenues), or it may simply be that the difference between the benefits and costs is sufficiently large that relatively small movements in costs do not greatly affect adoption.

In the United States firms with larger proportions of urban residents (that is, a more concentrated population) adopted more quickly than firms with more diffuse populations.[7] Oddly, firms with more rapidly growing urban populations actually adopted more slowly than their counterparts. In the international data, countries with a larger area adopted more slowly, although population density was not significant. Also, countries with larger labor forces adopted more slowly. Again, these measures are not directly comparable. However, all else equal, larger countries will tend to have the population split into more centers and those centers will tend to be more geographically diverse. This would make it relatively more expensive to obtain network externalities due to the necessity of upgrading the systems interconnecting each population center (the "long-haul" infrastructure). In the U.S. this long-haul infrastructure was largely provided by the interexchange carriers such as AT&T, which adopted digital technology rather rapidly. Accordingly, it was probably not a bottleneck in the U.S. for the local operating companies, but in other countries with a single company controlling both the long distance and local portions of the network, the issue is apparently more significant.

7 Conclusions

These results raise a number of issues. First, they provide empirical evidence on the direction of effect for some theoretically ambiguous determinants of adoption. Internationally, GDP and telecommunications infrastructure are both associated with earlier and faster adoption. Geographic area, larger numbers of people waiting for lines to be installed and larger labor forces are associated with later and slower adoption. These results hold across a wide variety of regulatory regimes, showing that economic pressures have real effects even where the industry is heavily regulated. The comparison with U.S. results also suggests that greater precision can be obtained by examining both the level and type of infrastructure.

Unless the type of infrastructure is controlled for, analyses of the levels of infrastructure may provide misleading results. For example, Roller and Waverman (2001) have examined the 1975-1990 period, which was an early period in the history of digital adoption. Only one third of their observations have any digital deployment whatsoever, and the average level of digital lines is only 7 percent.[8] However, there is a significant increase in digital deployment among many countries at the end of their time period. Roller and Waverman use both penetration and capital measures but do not control for the type of technology deployed. Two countries, one of which purchases analog lines, another of which upgrades analog lines to digital lines, may spend the same amount of money, and the upgrading country will experience a smaller increase in penetration, but the digital upgrades may well have a greater effect on productivity than the analog lines. The results

[7] This is not the same as average population density. This is closer to a measure of urbanization. A country can have relatively high population density but still have a predominantly rural economy. It can also have a relatively low population density but have virtually all of the population concentrated in a few cities (such as Australia).

[8] These figures are obtained through independent analysis of the data cited by Roller and Waverman.

here indicate that contemporaneous GDP is strongly correlated with the timing and rate of digital adoption. These results suggest that previous studies examining levels of infrastructure may be able to obtain greater statistical power by accounting for the type of infrastructure as well.

In the U.S., companies which still had large installed bases of electromechanical switches (that is, which had been slow to adopt analog systems) were found to adopt digital technology more quickly than those companies with large installed bases of analog switches. Unfortunately, the international data do not allow for this effect to be tested. There is at least some anecdotal evidence that certain Asia-Pacific countries may be bypassing widescale digital landline networks in favor of wireless networks (Schement and Forbes 2003; Melody 2005). While the results here suggest that countries which have been slow to adopt new technologies in the past will continue to be slow in the future, these anecdotes, and the relatively rapid transitions observed once adoption begins, offer some hope of solving the “digital divide,” where technological laggards remain permanently behind their neighbors (Campbell 2001). Some preliminary work has been done in this area with mixed results. Henten (2005) finds that total telecommunications investment in Denmark increased due to liberalization in 1996 to 2001 by more than three times, but then decreased considerably in 2002. Henten also finds that diffusion of new technologies in Demark was relatively rapid, but not more so than for other European countries that liberalized their telecommunications sectors later than Denmark. Similarly, a study by Jones Day and SPC Network for the ECTA (2004) finds that while regulatory factors and investment in European countries show strong and statistically significant relationships, the extent of regulatory improvements has been somewhat patchy. This area is ripe for further research.

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