Timing and determinants of local residential broadband adoption: evidence from Ireland

Sean Lyons
Economic and Social Research Institute, Whitaker Square, Sir John Rogerson's Quay, Dublin 2, Ireland and Department of Economics, Trinity College Dublin; email: sean.lyons@esri.ie

Abstract This article examines the time path of broadband adoption for households in areas that are offered broadband service for the first time and the socioeconomic characteristics of broadband users generally. Using cross-sectional data on broadband take-up and socioeconomic characteristics of small areas in Ireland, linked to GIS data on ADSL availability over time, I find that local penetration growth rates are elevated immediately after service is offered. Local growth rates then decline towards the national average, reaching it after about 3.6 years. The article also includes estimates of the effect of various household characteristics on adoption, finding effects broadly consistent with previous literature. Simultaneity in demand and supply are addressed using 2SLS regression.

JEL codes: L96, D12, R22
Key words: residential broadband demand, econometric analysis, speed of adoption

1. Introduction

The research question in this article concerns how quickly residential broadband adoption rises following an improvement in the local availability of broadband services and what socioeconomic factors influence the level of adoption in a small, low-density European country: Ireland. The expected time pattern of residential adoption following introduction of broadband services to an area affects the present value of the benefits from investment in a given area. Faster adoption implies a stronger case for investment, *ceteris paribus*. Information on the characteristics of adopters and non-adopters can also inform the case for public intervention in broadband supply as well as the scope for complementary policies such as educational measures.

This can be restated in practical terms: as broadband services are extended to cover "white space" areas, does local demand quickly converge with that of areas that have long been offered service (as customers satisfy pent up demand), or does it take time for customers to choose to take up service, perhaps because local network externalities are important? Adoption rates can affect commercial returns from such areas significantly. For example, in Ireland a report by the Comptroller and Auditor General found that take-up of the national scheme to provide broadband to unserved areas was "significantly weaker than expected at the outset of the scheme" (C&AG, 2011). In particular, the growth rate in the first year of the scheme was lower than anticipated. The outcome in this particular case may have been driven by other factors, not least the recession that coincided with the scheme, but knowing more about the expected local time path of adoption could help firms and policymakers planning future schemes of this kind.

Addressing this question requires data on who adopts broadband, their household characteristics and the local availability of broadband services over time. This article focuses on the Republic of Ireland, using data drawn from two main sources. The 2006 Census of Population in Ireland reported detailed small area population statistics for 3400 electoral divisions (EDs). For each ED, this includes the number of households with and without broadband services. In addition, there are a wide range of socioeconomic indicators such as the prevalence of each social class, level of educational attainment, age, employment status and sector, type of accommodation, PC ownership, etc.

The second dataset contains geographical panel data from 2001 to 2006 on 1060 fixed line local exchange areas in Ireland and the date at which each was enabled for ADSL services (for those that were enabled in the period).[1] These two datasets have been combined using geographical information system software (ArcGIS 10) to impute the average time since ADSL services were enabled for customers in each ED.

[1] ADSL refers to "asynchronous digital subscriber line", a technology and set of associated standards that permit high speed digital communications to be carried over copper telephony circuits.

I use regression analysis to explain the penetration of broadband at ED level in 2006, as a function of ED population characteristics, the average distance of residences from their local exchange (a proxy for quality of service) and the average time elapsed since ADSL was made available to households in each ED.

As well as broadband availability affecting the scope for adoption of services, it is likely that the expected level of adoption affects the order in which areas are enabled. This simultaneity between supply and demand factors is allowed for using the average number of residences served by the local exchanges in each area as an instrument for identifying the time since enabling, because it affects the supply side (via economies of scale in supply of ADSL) without having any obvious effect on household demand.

The next section of the article refers to some of the extensive past research on residential broadband adoption as a source of hypotheses about what factors affect broadband demand and supply. Section III describes the modelling approach, and Section IV discusses the data used. Section V describes the regression results and Section VI provides some conclusions.

2. Previous research on residential broadband adoption

A growing body of literature exists on the determinants of residential broadband demand and supply. Much of this work relies on discrete choice modelling of household data in a particular market, as in Rappoport *et al.* (2003). Another approach is to use cross-country data. For example, Billon *et al.* (2009) presents a cross country study of the determinants of ICT[2] diffusion using data from 142 low, middle and high income countries in 2004 and Jakopin and Klein (2011) examine data for 179 countries up to 2009. Survey data form the main source of information about how household competencies and attitudes affect use

[2] Information and communication technologies

of broadband services, e.g. Savage and Waldman (2005, 2009). Most studies using these approaches focus on the determinants of demand, without explicitly modelling supply factors. Other past studies have focused on the determinants of supply without explicitly modelling the simultaneity of demand. For example, Prieger (2003) uses cross-sectional data to estimate probit models on availability of broadband in US ZIP code areas.

This article adopts two relatively new methodological improvements. First, I model demand and supply of broadband together. Glass and Stefanova (2010) and Prieger and Hu (2008) are examples of this approach. An important advantage of these models is that they allow for the conditionality of broadband demand on local provision of service. This approach differs from papers that consider demand (e.g. Rappoport *et al.* 2003) or supply (Prieger 2003) in isolation. The second improvement, in common with Prieger and Hu (2008), is to take explicit account of the time pattern of exchanges being enabled rather than modelling the supply of broadband as a static process (as in Prieger 2003). This is essential to ask the question posed at the start of this paper: does time since enabling affect demand?

Existing studies identify a wide variety of factors that influence residential broadband demand and supply. Significant influences on demand include prices, reliability and quality of service, as well as a range of customer characteristics including income, age, education and technical ability. On the supply side, perhaps the most significant factor is urban/rural location. Population density more generally and the degree of competition in the market are also highlighted in the literature. The typical findings as to direction of effects are outlined below.

Household income is normally found to be a significant positive contributor to the rate of broadband adoption. The price of services, not surprisingly, tends to have a negative effect. Reliability and quality of service are less studied, but would be expected to increase adoption; for example, Prieger and Hu (2008) find a negative association between distance from the local exchange and adoption rates. They interpret this as a quality effect, as data speeds feasible with ADSL tend to fall with increasing line length. However, Glass and Stefanova (2010) report no statistically significant effect between mean distance to from exchange to customer and the decision to offer DSL service.

Education is generally found to have a positive effect on broadband adoption, as in Rappoport *et al.* (2003), Savage and Waldman (2005), Billon *et al.* (2009) for ICT generally, and ComReg (2009) for broadband in Ireland specifically. However, there are rare exceptions (e.g. some of the models in Prieger and Hu (2008) suggest that college graduates have lower broadband demand). Savage and Waldman (2009) emphasize the importance of technical ability as a positive influence on broadband access and use, as opposed to more general measures of educational attainment. In the context of Ireland, DCMNR (2006) also finds that the availability of technical skills in a household increases the uptake of broadband.

The international findings on the effect of age on broadband demand are somewhat more varied. For example, Rappoport *et al.* (2003) and Prieger and Hu (2008) show results from several models in which ADSL adoption is negatively associated with age. In contrast, Billon *et al.* (2009) find that in developing countries population age has a positive effect on ICT adoption. However, for developed countries it seems clear that the oldest age groups are less prone to adopt broadband than the rest of the population.

In common with earlier fixed line communications technologies, the ‘last mile’ of copper-based and fibre-based broadband networks is generally understood to exhibit strong economies of density. Forfás (2010), from the viewpoint of an Irish development agency, supports the view that investment in broadband infrastructure is crucially determined by population density and urbanization. Their work highlights Ireland’s weakness on these metrics, with a combination of a high proportion of people living in rural areas (39%) and a low population density of 62 inhabitants per square kilometre. Jakopin and Klein (2011) find a strong positive association between urbanisation and the fixed broadband launch lead time internationally. The evidence on this is not entirely one-sided, however: Whitacre and Mills (2007) use U.S. population survey data from 2000 to 2003 to examine the high speed access divide between rural and urban areas. They find that differences in education and income between rural and urban areas account for the divide and not infrastructure *per se*.

Finally, concerning the effect of time since a local exchange was enabled on broadband adoption, Prieger and Hu (2008) find a weak, but positive and highly statistically significant effect, using US data.

There are fairly consistent messages from the literature concerning the factors that incline residential customers to take up broadband. Past research typically identified price (negative), quality (positive), education (positive), technical skills (positive), competition (positive) and age (negative) as the main factors driving broadband demand. Population density or (related to it) rural/urban location are the most frequently cited supply factors, with higher density normally associated with increased broadband availability.

3. Modelling approach

This section describes the model and estimation method used in the article.

Theoretical model

The theoretical model behind this analysis is straightforward. I assume that a household's potential utility from adopting broadband services is a function of certain socioeconomic characteristics. This is in line with the literature. However, in an extension to the usual approach, I allow for the possibility there is some lag between the service becoming available to a given household and the decision to adopt. There are many possible reasons for such a lag (e.g. local network externalities, imperfect information or behavioural biases). To give a few illustrative examples, potential broadband users may wait to adopt the service until their neighbours have it, until locally-generated content is available, or until they learn about its potential via local social networks. The available data will not allow me to explore the reasons for a lag, only to measure its duration if it is present.

I assume here that there is only one provider of broadband network access, which is a reasonable simplification for ADSL services in Ireland during the period being studied. Of course, both demand and supply choices might also be influenced by the presence of other technologies, particularly fixed wireless and cable-based services, that were being introduced during this period. Unfortunately, there is little public information on the rollout and take-up pattern for these services during the period.

The household will adopt broadband if its expected utility is high enough, but obviously only if broadband is available to it. On the supply side, offering broadband services in a local area requires investment, for example installation of modems in local exchanges or wireless base stations. Local areas are only enabled for broadband when the expected stream of future profits from doing so becomes positive. The cost of supplying broadband is assumed to exhibit economies of density, so assuming demand rises over time, more densely populated areas will be enabled first, *ceteris paribus*.

The remainder of this section sets out the model in more formal terms. The demand model can be summarized thus:[3]

$$B_{ijt} = f\left(\mathbf{X}_i, P_t, \mathbf{S}_{jt}, t - t_j^0\right) \text{ for each household } i \text{ in area } j \text{ at time } t \qquad (1)$$

[3] This is essentially the demand model in Taylor (1994), Ch.2, expressed with a spatial dimension appropriate to the data used in this study.

where B is a 1/0 indicator of whether broadband services are taken up, $\mathbf{X}$ is a vector of socioeconomic characteristics, P is the geographically averaged unit price, $\mathbf{S}$ captures the quality of service and content that is available to broadband customers. The quality of content may be growing over time but is assumed to be uniform across areas at any given time, while other aspects of quality may vary across areas. t_j^0 is the earliest time period that broadband services were enabled in the household's area. A household's propensity to adopt broadband should be negatively associated with the price and positively associated with its quality and the time elapsed since enabling.

As the available data (discussed in the next section) are averages for geographical areas, the demand function can be expressed as:

$$\frac{\sum_{i=1}^{N_j} B_{ijt}}{N_j} = g\left(\mathbf{V}_j, P_t, \mathbf{S}_{jt}, t - t_j^0\right) \qquad (2)$$

where N is the number of households in the area, $\mathbf{V}$ is a matrix containing the shares of each socioeconomic characteristic in the population of the area and g is a function. When I come to estimate this function econometrically, most price and quality effects will form part of the constant, since they are assumed not to vary across areas in a given period. However, I will be able to control for the average distance of residential addresses from the local exchange in each area, which should be correlated with the average quality of ADSL service in the area, as per Prieger and Hu (2008).

The choice as to whether to enable broadband in an area can be expressed as:

$$\begin{aligned} &E_{jt} = 1 \text{ if } \sum_{k=t}^{\infty} h\left(\sum_{i=1}^{N_j} B_{ijk}, P_k, C_j\right)(1+d)^{-(k-t)} > 0 \\ &E_{jt} = 0 \text{ otherwise} \end{aligned} \qquad (3)$$

where E is a 1/0 indicator of whether broadband services are enabled in the area, k is an index of future time periods, C is the relative unit cost of supplying broadband in the area, d is a discount rate and h is a function. The absolute average cost of supplying broadband will vary over time, but I assume that access regulation is applied that imposes a fixed relationship between the average cost and price charged, so the cost need not enter the model separately.[4] The choice of enabling an exchange should be positively associated with price and demand, but negatively associated with the relative cost of supplying the area. Adoption of broadband in an area will obviously be affected by whether the area has been enabled for ADSL service, but supply can also affect demand via the time elapsed since enabling:

$$T_j = t - t_j^0 = m\left(\mathbf{V}_j, \mathbf{P}, \mathbf{C}_j, \mathbf{S}_j,\right) \qquad ` \qquad (4)$$

where $\mathbf{P}$, $\mathbf{S}$ and $\mathbf{C}$ are vectors of past and expected future prices, quality/content levels and relative unit costs; m is a function. The effects of $\mathbf{P}$ and some elements of $\mathbf{S}$ (e.g. the quality of available content) will fall into the constant term when this equation is estimated using cross-sectional data. I assume that $\mathbf{C}$ is inversely proportional to the number of connections to the local exchange. For brevity, hereafter I refer to time since enabling $\left(t - t_j^0\right)$ as T_j. Equations 2 and 4 can be estimated using available data using econometric models discussed in the next sub-section.

Econometric models

Demand and supply of access to residential broadband services are determined simultaneously. Although I am mainly interested in the demand side, estimating the

---

[4] The incumbent operator's supply of broadband access services was subject to wholesale price control and other regulatory measures by Ireland's Commission for Communications Regulation (ComReg) throughout this period; see ComReg (2010a and 2010b).

demand equation in isolation would lead to endogeneity problems. Supply and demand are simultaneously determined: suppliers will first enable exchanges in areas where demand is likely to be high, while only customers in enabled areas can take up DSL services. Ignoring this source of endogeneity could lead to misinterpretation of the coefficients on the demand function. For example, if a regression indicated that a factor strongly predicts demand, it would not be obvious whether this was a genuine causal effect or whether the factor actually strongly influences supply but has no direct effect on demand. Fortunately, there are good instruments for the cost of supplying broadband in a local area: the number and squared number of residences served by each local exchange. I use these instruments to identify the supply function in a two-stage least squares regression, with the demand equation as the second stage. Demand is thus estimated conditional on supply conditions.

First stage (supply) regressions

Because demand may have a non-linear relationship to the timing of broadband supply, I estimate two first stage regressions based on Equation 4 above. One takes as its dependent variable the average time (in years) since ADSL was enabled in the local exchanges to which addresses in each ED are connected, and the second models the squared average time. The two supply regression equations are summarised in Equations 5 and 6 below, with vectors of regression coefficients ($\boldsymbol{\beta}^{[\mathbf{v},\mathbf{c},\mathbf{s}]}$,$\boldsymbol{\gamma}^{[\mathbf{v},\mathbf{c},\mathbf{s}]}$), intercept terms ($\alpha, \chi$) and random error terms (ε, λ):[5]

$$T_j = \alpha + \boldsymbol{\beta}^{\mathbf{v}}\mathbf{V}_j + \boldsymbol{\beta}^{\mathbf{c}}\mathbf{C}_j + \boldsymbol{\beta}^{\mathbf{s}}\mathbf{S}_j + \varepsilon \qquad (5)$$

$$T_j^2 = \chi + \boldsymbol{\gamma}^{\mathbf{v}}\mathbf{V}_j + \boldsymbol{\gamma}^{\mathbf{c}}\mathbf{C}_j + \boldsymbol{\gamma}^{\mathbf{s}}\mathbf{S}_j + \lambda \qquad (6)$$

[5] Intercept and error terms are shown as the same letters for simplicity but are unrelated to one another.

As instruments for the varying costs of supplying ADSL services across EDs ($\mathbf{C}_j$), I include the level and squared values of the average number of residential addresses per exchange. Since there are fixed costs of ADSL supply at exchange level, total costs should be inversely associated with the number of subscribers served by an exchange, and they might have a positive association with the square of subscriber density (implying positive but diminishing economies of density). No data were available on other factors that might affect the local cost of enabling exchanges, such as the cost of additional backhaul.

All other explanatory variables employed in the demand model are also included in the first stage regressions. These variables are discussed in more detail below.

Second stage (demand) regression

The dependent variable in the second stage regression (based on Equation 2 above) is the share of addresses in each ED that had obtained access to broadband services as of 23 April 2006. The survey question used for the purpose of the analysis is:

Does your household have access to the Internet?

> *Yes, broadband connection*
>
> *Yes, other connection*
>
> *No*

Source: Central Statistics Office (2006a)

This is based on self-reported census data, so it is not possible to provide a strict definition of what is included within the term “broadband” in this article. As a consequence, one possible source of measurement error in our models is different views among respondents about what constitutes a broadband connection.

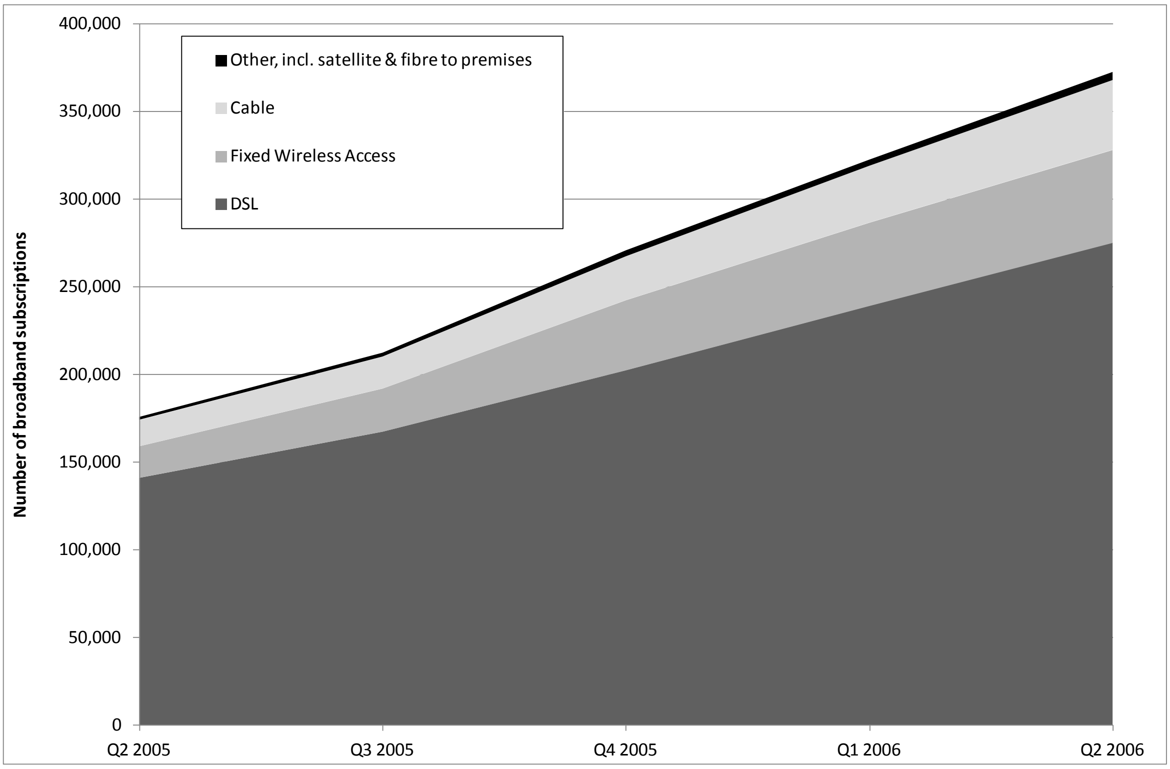
The second stage (demand) regression equation is summarised in Equation 7 below with vectors of regression coefficients ($\boldsymbol{\delta}^{[\mathbf{v},\mathbf{s},t,tsq]}$), an intercept term ($\kappa$) and a random error term (μ):

$$\frac{\sum_{i=1}^{N_j} B_{ijt}}{N_j} = \kappa + \boldsymbol{\delta}^{\mathbf{v}}\mathbf{V}_j + \boldsymbol{\delta}^{\mathbf{s}}\mathbf{S}_j + \delta^{t}\hat{T}_j + \delta^{tsq}\hat{T}_j^2 + \mu \qquad (7)$$

The predicted time and squared time since enabling of ADSL in each ED, as estimated in the first stage regressions, are included as regressors here. Prices of retail broadband services are set nationally in Ireland (ComReg, 2011), but because coverage of different operators' services is not completely uniform across the country, average prices for available services do vary slightly at county level. In 2011 the gap between average advertised prices of services offered in the highest and lowest priced counties was about €2 and the average price was €51 per month, with more urban counties tending to have slightly lower prices than the more rural counties (Lyons and Savage, 2013). In any event, spatially differentiated information on broadband prices is not available for Ireland during the sample period, so own-price and cross-price terms cannot be included in the regressions. To the extent that demand is price elastic, omission of this effect could lead to some upward bias in the absolute value of coefficients related to population density, such as time since enabling of exchanges and average line lengths. This is because urban areas have higher population density and were also probably offered slightly lower average prices.

There is also no publicly available information on the geographical rollout of alternative infrastructures over time in Ireland. However, in mid 2006 DSL served most broadband connections in Ireland, as shown in Figure 1.

Figure 1: Broadband subscriptions in Ireland by platform



Source: ComReg (2006)

The average quality of ADSL in an area, proxied by the average distance of residences from their local exchange, should have a positive association with broadband penetration.

A large number of demand-shifter variables are included, based on EDs' socio-economic characteristics. Details are provided in the next section. Previous research suggests that there should be associations between residential broadband demand and education (positive), age (negative), income (positive), occupational/social class (positive, as a proxy for long run income and assets) and PC ownership (positive). In addition, one might expect to see positive effects from the shares of people in an area working from home or born abroad (with the latter serving as a proxy for likely demand for long-distance communications). Jakopin and Klein (2011) found a statistically significant positive association between service sector activity and fixed broadband penetration; it is possible to check for this using commercial sector employment as a proxy.

The proportion of first time job seekers in an area could have a positive or negative association with having a broadband connection. There is conflicting evidence about whether broadband access at home reduces the cost of job search or improves employment outcomes (Beard *et al.* 2012; Kuhn and Skuterud 2004), while other research has found a negative association between job search and continued use of the internet (Kim 2011).

Finally, I include the share of persons in each area who speak Irish at least once per day outside a school context. Since more internet content is in English than in Irish, one might expect a preference for speaking Irish to have a negative association with demand for broadband services. However, Prieger and Hu (2008) found that the use of non-English languages increased demand for broadband in US households, although they also found a countervailing negative association with being in a household where no one speaks English as a first language.

Because these regressions are estimated on cell means, I weight each ED-level observation by the population in the ED to adjust for the unequal variances across cells. The linear two-stage least squares estimator is used.

4. Data employed

The article draws upon two main sources of data for modelling Irish residential broadband adoption. First, local average broadband take-up and socioeconomic characteristics are taken from the Central Statistics Office Census Small Area Population Statistics ("SAPS"; Central Statistics Office 2006b). These data are at electoral division (ED) level, covering 3392 areas.[6] Most EDs in the country are included in the analysis, and they average 20.6

[6] A small number of EDs were omitted or amalgamated to allow matching of data sources. Details are available on request from the author.

square kilometres in size and 1240 in population. The SAPS dataset provides a snapshot of the position as at 23 April 2006 (the day of the most recent Irish census).

The second main source is panel data on ADSL availability in 1060 local exchange areas from 2001-2006. This dataset was provided by the main Irish fixed line carrier eircom, on foot of a request from the Commission for Communications Regulation. I assume that ADSL was available in an area from the date the local exchange was enabled. More detail is given below on how these data were assembled.

I also use data on average disposable income per capita at county level, published by the CSO. ED-level household income data would have been preferable, but this proxy is the best currently available. Table 1 below summarizes the variables drawn from each of these sources.

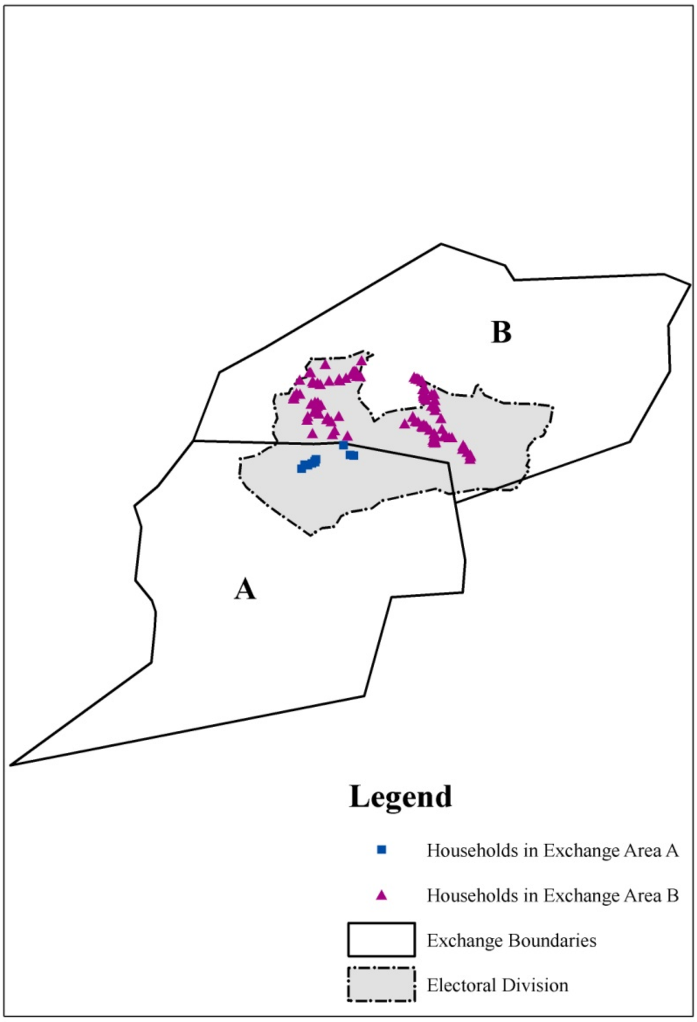
[Please insert Table 1 here]

GIS analysis was required to map data on ADSL availability to EDs. This was done by identifying the local exchange area in which every residential address in Ireland was located, using a digital map provided by eircom. From this it was straightforward to calculate the Euclidean distance of each residential property from its local exchange and the average number of residences in each local exchange area. These were then averaged within EDs to give the average distance from local exchange and addresses per local exchange variables.

I then calculated the time since ADSL was made available for each address based on the ADSL availability date of the relevant local exchange. These times were calculated from the date of enabling of each local exchange to the date of the census: 23 April 2006.

Addresses in non-enabled zones were assigned a zero duration since enabling. Finally, I calculated the average time since ADSL enabling for all addresses in each ED. Figure 2 illustrates how this was done. Residential properties in the two exchange areas (shown as A and B) were each assigned the relevant enabling dates for their exchanges, and then the average time since enabling was calculated across all properties in the ED (the shaded region).

Figure 2: Broadband subscriptions in Ireland by platform



An animated map showing the geographical pattern of residential ADSL availability in Ireland from 2001-2008 is shown here. [Please put a hyperlink to the animation of broadband rollout on the word 'here'. In the print version, please replace "shown here" with "available at http:\\www…. The animation is stored in the attached file "Residential ADSL rollout in Ireland 2001-2008.avi"]

Descriptive statistics for the variables used in the article are shown in Table 2.

[Please insert Table 2 here]

5. Results

Regression results are set out in Tables 3 and 4 (first stage; supply of xDSL services) and Table 5 (second stage; demand for broadband). There are two first stage regressions, relating separately to the level and squared value of the time elapsed since local exchanges were enabled.

[Please insert Table 3 here]

[Please insert Table 4 here]

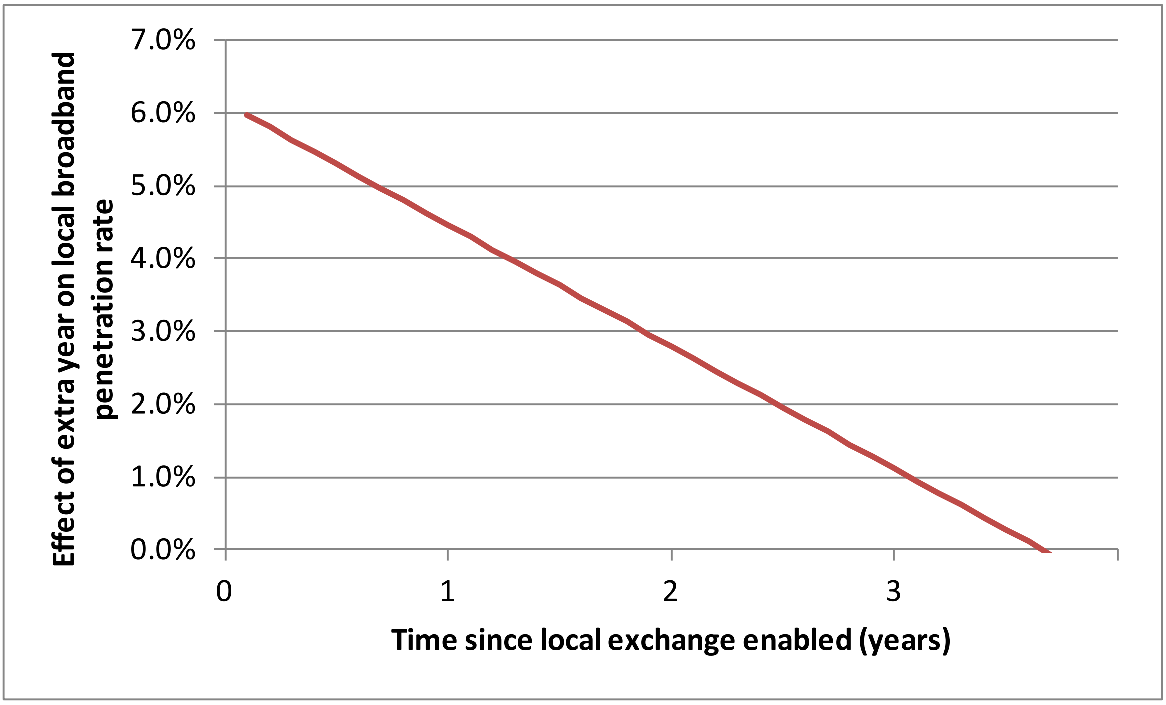
[Please insert Table 5 here]

Time pattern of reaction to local ADSL supply

On average, an extra year since local enabling of ADSL is associated with an increase of 5.2 percentage points in average ED-level broadband take-up (Table 5, coefficients on *AvgTimeSinceADSLhat* and its squared value) for the EDs in our sample. This effect is significant at the 1% level, and it is sizeable when compared to the 10.6% average ED-level broadband penetration rate in the sample. In other words, I find evidence that areas enabled for longer had higher broadband adoption. Areas that were not supplied with ADSL in the sample period report an average broadband penetration rate of 5.3%, which must be mainly cable and fixed wireless services.

The impact of additional time since enabling itself varies over time. The first year since local enabling provides about a 5 percentage point increase in local broadband adoption, and the effect declines thereafter. This is illustrated in Figure 3 below. The results imply that the boost to growth rates following local enabling has run its course after 3.6 years on average.

Figure 3: Marginal effect of extra ADSL availability in an ED on the household broadband penetration rate, with varying lags



I now turn to other determinants of broadband demand and ADSL supply, starting with demand as this is the main focus of the article before turning to the supply results.

Demand equation

The results for the second stage (demand) equation shown in Table 5 are broadly in line with expectations. The average distance of households from the local exchange has a weak but highly statistically significant negative association with broadband take-up, which makes sense since it is a proxy for service quality.

Areas where household reference persons tend to be in “lower” occupational/social classes or have only a lower secondary level education tend to have lower broadband penetration. Primary education is a surprising exception to this pattern, having a positive coefficient. As expected, areas where fewer households have PCs (or do not state whether they have them) are less prone to take up broadband and persons living in houses rather than other types of accommodation are more likely to take up broadband. The share of people in an ED seeking their first jobs has a strong positive association with broadband take-up.

Areas with a high proportion of persons working in the Commercial sector (the reference category) have higher broadband take-up than those dominated by other sectors. The log of disposable income shows a small but statistically significant positive effect: for every 10% increase in disposable income, the model implies a 1.8 percentage point increase in local broadband adoption.

Surprisingly, the variable capturing the share of persons working from home has a negative and statistically significant coefficient. However, there is a high correlation in the Irish Census between working at home and working in agriculture. Indeed, if we drop the working from home variable from the regression, the coefficient on working in agriculture becomes significant and negative. Thus the working from home coefficient probably does not tell us much about people who might be working on line from home.

The shares of Irish speakers and those over 15 who are still in education are positively associated with broadband, while the share of the population made up by couples with children is associated with lower broadband adoption than most other family types.

Supply equations

The first stage (supply) equations were estimated principally to correct the demand equation for possible endogeneity bias. Nevertheless, these results may be of interest in their own right. I focus here on Table 3, showing the regression for average time since ADSL was enabled. ADSL enabling takes place earlier in areas with a high proportion of commercial sector employees, foreign born persons, people working from home, and higher incomes. It takes place later in areas with larger proportions of households without children, foreign born people and households in which the reference person is educated to lower secondary level.

The number of residences in an exchange area has the expected positive sign in levels and negative sign in the squared term, consistent with positive but diminishing economies of density. Both terms are highly statistically significant. The coefficients in Table 3 imply an expectation that economies of density for ADSL technology are maximized at about 18 370 residential addresses in an exchange area.

Other terms on the supply side are less easy to interpret. There is some evidence of an unexpected negative association between areas with a high proportion of undergraduate degree holders and ADSL supply. ADSL seems to be enabled sooner in areas with low PC ownership or higher proportions of 45-64 year olds, but later in areas with a larger number of people working from home.

The model of squared time since enabling (Table 4) gives similar results to the model in levels, but there are some differences. The squared model shows lower adoption in areas with more people in the “lowest” occupational/social classes and has a statistically significant positive association with the share in the oldest age group (65+), whereas the levels model had no statistically significant result for this group.

6. Conclusions

Even in jurisdictions where matched data are not collected on demand and supply of broadband services, it may be possible to estimate market parameters by linking other spatially-coded datasets. This article reports results from a two-stage model of broadband demand and ADSL supply, primarily using small area data from the Census of Population and GIS data from the incumbent fixed line operator on the location of local exchanges and the ADSL rollout over time.

It takes time for households in an area to take up broadband services once they are offered, even apart from any tendency for broadband demand to rise over time across the whole population. The first year since local enabling provides more than a 5 percentage point increase in local broadband adoption, and the effect declines thereafter. The boost to growth rates following local enabling has run its course after 3.6 years on average. Commercial suppliers planning to roll out services and public bodies contemplating subsidies or universal service provisions for extensions to broadband network should take the expected time profile of adoption into account.

The main findings on the socioeconomic determinants of broadband supply and demand are summarised in Table 6 below. These results are broadly in line with previous research in other countries. This suggests that the strategy of using geographically linked datasets for demand and supply can allow one to assemble a reasonable model of the market.

[Please insert Table 6 here]

This analysis benefited from availability of geographically matched data on the supply of ADSL and socioeconomic data including take-up of broadband. Controlling for variations in supply is important when estimating the determinants of demand, and this is not always done in the literature due to data limitations.

However, there are also some shortcomings in the available data. Panel data at household level would have been preferable to cross-sectional data on areas (although it was possible to include the time dimension of ADSL availability). It would be interesting to measure the effects discussed here in a jurisdiction where household level panel data on actual (as opposed to perceived) availability and use of broadband services could be obtained.

If data were available on the geographical rollout of fixed wireless and cable broadband over time, it would be useful to examine how these infrastructures interacted with ADSL on both the supply and demand sides (at least in jurisdictions where competing infrastructures serve a significant share of the market).

There is also no information on household incomes at small area level in Ireland, so county-level income data were included instead. However, small area data on occupational/social class and educational attainment should have captured much of the income variation across EDs. Finally, if data were available on spatial patterns in the average price of broadband service offerings, this would help rule out possible bias due to the correlation between prices and population density.

Acknowledgements

The author would like to thank Sharon Walsh, Alice Casey and Niamh Crilly for research assistance and Patricia Dowling and John Lysaght for help in obtaining data. Two anonymous referees, Laura Malaguzzi Valeri, Paul Walsh and Paul Gorecki provided helpful comments on drafts, and I am grateful for comments received on earlier drafts at the 2010 European Regional Conference of the International Telecommunications Society and at an ESRI seminar. This research was funded by the ESRI Programme of Research in Communications, with contributions from Ireland's Department for Communications, Energy and Natural Resources and the Commission for Communications Regulation. The sponsors had no role in the design of the study; the collection, analysis, and interpretation of data; the writing of the report; or the decision to submit the paper for publication. The usual disclaimer applies.

References

Beard TR, Ford GS, Saba RP, Seals RA Jr (2012) Internet use and job search, Telecommun Policy 36:260-273.

Billon M, Marco R, Lera-Lopez F (2009) Disparities in ICT adoption: A multidimensional approach to study the cross-country digital divide, Telecommun Policy 33:596-610.

Central Statistics Office, 2006a, Census form. URL: http://www.cso.ie/en/media/csoie/census/documents/censusform_2006.pdf

Central Statistics Office, 2006b, Census Small Area Population Statistics. URL: http://census.cso.ie/censusasp/saps/boundaries/saps.htm

Commission for Communications Regulation (ComReg) (2006), Quarterly Key Data - September 2006: Raw Data. URL: http://www.comreg.ie/_fileupload/publications/ComReg0652b.xls

Commission for Communications Regulation (ComReg) (2009) Residential and Business Internet Connectivity: Irish and European experience, Document 09/84, 30 October. URL: http://www.comreg.ie/_fileupload/publications/ComReg0984.pdf

Commission for Communications Regulation (ComReg) (2010a) Market Review: Wholesale Broadband Access (Market 5), Consultation and Draft Decision, Document No: 10/81, 01 October. URL: http://www.comreg.ie/_fileupload/publications/ComReg_1081.pdf

Commission for Communications Regulation (ComReg) (2010b) Market Review: Wholesale (Physical) Network Infrastructure Access (Market 4), Response to Consultations and Decision, Document No: 10/39, 20 May. URL: http://www.comreg.ie/_fileupload/publications/ComReg1039.pdf

Commission for Communications Regulation (ComReg) (2011) Market Review: Wholesale Broadband Access (Market 5), Response to Consultations and Decision, Document No: 11/49, 8 July. URL: http://www.comreg.ie/_fileupload/publications/ComReg1149.pdf

Comptroller and Auditor General (C&AG) (2011) Report of the Comptroller and Auditor General, Volume 2, Accounts of the Public Services, 2010, Vote Management. URL: http://www.audgen.gov.ie/documents/annualreports/2010/2010_Volume_2_EN%281.04%29.pdf

Department of Communications, Marine and Natural Resources (DCMNR) (2006) Broadband Demand: A Review of Demand in the Irish Broadband Market, January. URL: http://www.dcenr.gov.ie/Communications/Communications+Development/Next+Generation+Broadband/Broadband+Demand+Report.htm

Forfás (2010) Ireland's Broadband Performance and Policy Actions, January. URL: http://www.forfas.ie/media/forfas100122-Broadband-Benchmarking-Ireland.pdf

Glass V, Stefanova S (2010) An empirical study of broadband diffusion in rural America, J Regul Econ 38:70-85.

Jakopin NM, Klein A (2011) Determinants of broadband internet access take-up: country level drivers, info 13:29-47.

Kim, S (2011) The diffusion of the Internet: Trend and causes, Soc Sci Res 40 (2):602-613.

Kuhn P, Skuterud, M (2004) Internet job search and unemployment durations. Am Econ Rev 94 (1):218-232.

Lyons S, Savage M (2013) Choice, price and service characteristics in the Irish broadband market, Int J Manag and Netw Econ 3 (1): 1-21.

Prieger JE (2003) The Supply Side of the Digital Divide: Is There Equal Availability in the Broadband Internet Access Market?, Econ Inq 41:346-363

Prieger JE, Hu WM (2008) 'The broadband digital divide and the nexus of race, competition, and quality', Inf Econ and Policy 20:150-167.

Rappoport PN, Kridel DJ, Taylor LD, Alleman JH, Duffy-Deno KT (2003) Residential demand for access to the Internet, in Madden G, (ed), *Emerging Telecommunications Networks: The International Handbook of Telecommunications Economics, Volume II*, Edward Elgar, Cheltenham, UK, 55-72.

Savage SJ, Waldman D (2005) Broadband Internet access, awareness, and use: Analysis of United States household data, Telecommun Policy 29:615-633.

Savage SJ, Waldman DM (2009) Ability, location and household demand for Internet bandwidth, Int J Ind Organ 27:166-174.

Taylor, LD (1994), *Telecommunications Demand in Theory and Practice*, Kluwer Academic Publishers, Dordrecht.

Whitacre BE, Mills BF (2007) Infrastructure and the rural-urban divide in high-speed residential internet access, Int Reg Sci Rev 30:249-273.

Tables

Table 1: Variable descriptions by source

Variable	Description
Exchange characteristics and eircom ADSL rollout by local exchange area, 2001-2006, mapped to EDs using the An Post Geodirectory	
Average years since ADSL was enabled	Average time since ADSL was enabled for residential addresses in each ED
Average distance from local exchange	Average Euclidean distance of residential addresses from local exchange in each ED
Average addresses per local exchange	Average number of residential addresses in the local exchange areas that overlap with each ED
Census Small Area Population Statistics, 2006, CSO	
Broadband access	Share of ED households with broadband internet access
PC ownership	Share of ED households with a personal computer
Accommodation type	Share of ED households residing in each of five accommodation types
Household composition	Share of ED households in each of five composition groupings
Highest level of education completed	Share of ED population aged 15 and older in each of seven categories for highest level of education completed
Principal economic status	Share of ED population aged 15 and older in each of eight economic status groupings
Age group	Share of ED population in each of five age bands
Industry	Share of ED working population in each of eight industry groupings
Occupational/Social Class	Share of ED household reference persons in each of six groupings
Irish speakers	Share of ED population over 3 years old who speak Irish at least daily (outside school)
Foreign born	Share of ED population born outside Ireland
Persons working from home	Share of ED working population that works mainly from home
Persons still receiving education	Share of ED population aged 15 and older still in education
Population density	Population of ED in 2006 divided by area (in Km^2)
County Incomes and Regional GDP, 2006, CSO, published 24 February 2009	
Average disposable income per capita (county level)	Average disposable income per capita (€) in 2006 for county in which each ED is located in the sample

Table 2: Summary statistics (individual observations are at electoral division level, 3388 observations)

Variable description	Variable name	Mean	Std Dev	Min.	Max.
Dependent variables					
Average years since ADSL enabled	*AvgTimeSinceADSL*	1.07	1.45	0	4.82
Broadband access	*BroadbandShare*	0.106	0.0980	0	0.614
PC ownership					
Yes	*PCOwnerYes*	0.541	0.0992	0.151	0.878
No	*PCOwnerNo*	0.439	0.0972	0.108	0.818
Not stated	*PCOwnerNS*	0.0198	0.0175	0	0.176
Accommodation type					
House	*AccHouse*	0.924	0.114	0.0244	1
Flat/apartment	*AccFlat*	0.0443	0.103	0	0.921
Bedsit[7]	*AccBedsit*	0.00285	0.0104	0	0.162
Caravan/Mobile home	*AccOther*	0.00903	0.0127	0	0.158
Not stated	*AccNS*	0.0195	0.0175	0	0.167
Household composition					
Single person	*CompSingle*	0.224	0.0681	0.0513	0.633
Couple	*CompCouple*	0.183	0.0400	0.0286	0.366
Single & children	*CompSingle&k*	0.0926	0.0370	0	0.433
Couple & children	*CompCouple&k*	0.391	0.0961	0.0137	0.677
Other family	*CompOthFam*	0.0598	0.0243	0	0.250
Other non-related	*CompOtherNR*	0.0497	0.0458	0	0.490
Highest level of education completed					
None	*EduNone*	0.00530	0.00855	0	0.220
Primary	*EduPrimary*	0.212	0.0807	0.0155	0.581
Lower Secondary	*EduLwrSec*	0.223	0.0512	0.0263	0.383
Upper Secondary	*EduHighrSec*	0.378	0.0612	0.131	0.578
Primary Degree	*EduDegree*	0.0932	0.050	0	0.383
Postgraduate	*EduPostgrad*	0.0492	0.0337	0	0.255
Not stated	*EduNS*	0.0393	0.0340	0	0.377
Principal economic status					
At work	*EconWork*	0.558	0.0648	0.205	0.763
Looking for first regular job	*EconLk1stJob*	0.00659	0.00597	0	0.0530
Unemployed	*EconUnemp*	0.0379	0.0232	0	0.247
Student	*EconStudent*	0.0977	0.0356	0.0163	0.679
Looking after home/family	*EconHome*	0.133	0.0307	0.0269	0.268
Retired	*EconRetired*	0.123	0.0401	0.0086	0.357
Unable to work due to sickness/disability	*EconDisabled*	0.0412	0.0213	0	0.256
Other	*EconOther*	0.00322	0.00683	0	0.278

[7] A bedsit is a small flat akin to a studio, normally including a single bedroom/sitting room. Limited cooking facilities are sometimes available, but the bathroom and lavatory are usually shared.

Variable description	Variable name	Mean	Std Dev	Min.	Max.
Age group					
0 -14 years	*Age0-14*	0.208	0.0448	0.0076	0.389
15 – 24 years	*Age15-24*	0.136	0.0370	0.0417	0.607
25 – 44 years	*Age25-44*	0.286	0.0521	0.137	0.551
45 – 64 years	*Age45-64*	0.241	0.0429	0.0697	0.409
65+ years	*Age65+*	0.129	0.0437	0.0079	0.372
Industry (of those in employment)					
Agriculture, Forestry, Fishing	*IndAgric*	0.112	0.0813	0	0.517
Building & Construction	*IndBuilding*	0.134	0.0482	0.0126	0.396
Manufacturing	*IndManufac*	0.141	0.0526	0	0.405
Commerce & Trade	*IndCommerce*	0.215	0.0694	0	0.507
Transport & Communications	*IndTransComms*	0.0454	0.0228	0	0.235
Public Admin	*IndPublic*	0.0473	0.0245	0	0.314
Professional Services	*IndProfess*	0.164	0.0432	0.0375	0.401
Other	*IndOther*	0.141	0.0643	0	0.573
Employment/Social Class (of household reference person)					
ABC: Employers & managers; Higher professional; Lower professional	*SocialClassABC*	0.246	0.103	0.0212	0.704
D: Non-manual	*SocialClassD*	0.124	0.0478	0	0.307
EF: Manual skilled; Semi-skilled	*SocialClassEF*	0.194	0.0581	0	0.423
GJ: Unskilled; Agricultural workers	*SocialClassGJ*	0.0584	0.0304	0	0.267
HI: Farmers; Own account workers	*SocialClassHI*	0.203	0.114	0	0.556
Z: Others gainfully occupied & unknown	*SocialClassZ*	0.175	0.0733	0	0.600
Other variables					
Irish speakers	*IrishSpeakers*	0.0147	0.0464	0	0.548
Foreign born	*ForeignBorn*	0.120	0.0659	0	0.598
Persons working from home	*HomeWorkers*	0.055	0.0358	0	0.245
Persons over age 15 still receiving education	*PersStillEducat*	0.109	0.0385	0.0261	0.660
Disposable Income per capita (county level)	*AvgIncome*	19 800	1518	17252	23226
Average distance from local exchange	*ExchangeDist*	2952	1680	140	13435
Average addresses per local exchange	*ExchangeSize*	3316	4775	107	27237

Table 3: First stage regression: dependent variable is *AvgTimeSinceADSL*; 3388 observations

Variables	Coef.	Robust S.E.
Ln(ExchangeDist)	-0.0940	0.0343***
PCOwnerYes	[REF]	
PCOwnerNo	0.799	0.455*
PCOwnerNS	-1.31	1.42
SocialClassABC	[REF]	
SocialClassD	1.05	0.726
SocialClassEF	-0.346	0.553
SocialClassGJ	-2.35	0.781***
SocialClassHI	-0.834	0.485*
SocialClassZ	-1.02	0.486**
EconWork	[REF]	
EconLk1stJob	0.704	3.48
EconUnemp	-1.59	1.12
EconStudent	1.75	1.45
EconHome	-1.13	0.844
EconRetired	-1.00	0.959
EconDisabled	-1.88	0.981*
EconOther	-0.11	1.50
AccHouse	[REF]	
AccFlat	0.259	0.264
AccBedsit	2.61	1.09**
AccOther	0.0863	1.31
AccNS	1.32	1.26
Age0-14	-1.68	0.968*
Age15-24	-2.05	1.35
Age25-44	[REF]	
Age45-64	1.41	0.651**
Age65+	1.47	1.02
IndAgric	-1.85	0.661***
IndBuilding	-2.45	0.595***
IndManufac	-3.44	0.572***
IndCommerce	[REF]	
IndTransComms	-2.27	1.09**
IndPublic	-1.61	0.878*
IndProfess	-2.68	0.566***
IndOther	-2.09	0.622***
CompSingle	-1.45	0.515***
CompCouple	-1.55	0.603***
CompSingle&k	1.90	0.692***
CompCouple&k	[REF]	
CompOthFam	1.07	0.793
CompOtherNR	0.0838	0.739
EduNone	0.124	1.48
EduPrimary	0.106	0.437
EduLwrSec	-1.17	0.559**
EduHighrSec	[REF]	
EduDegree	-1.48	0.847*
EduPostgrad	1.32	1.17
EduNS	1.11	0.714
IrishSpeakers	0.589	0.331*
ForeignBorn	1.57	0.353***
PersStillEducat	0.223	1.42
HomeWorkers	-2.90	0.834***
Ln(AvgIncome)	2.56	0.334***
ExchangeSize	0.000363	0.0000128***
ExchangeSize^2	-9.88E-09	4.42E-10***
Constant	-21.3	3.42***

*Note: *, ** and *** denote significant at the 10%, 5% and 1% level respectively. Data sources: see Table 1 above.*

Table 4: First stage regression: dependent variable is *AvgTimeSinceADSL^2*; 3388 observations

Variables	Coef.	Robust S.E.
Ln(ExchangeDist)	-0.955	0.223***
PCOwnerYes	[REF]	
PCOwnerNo	1.20	2.55
PCOwnerNS	-1.17	9.28
SocialClassABC	[REF]	
SocialClassD	4.42	4.27
SocialClassEF	0.973	3.39
SocialClassGJ	-5.26	4.26
SocialClassHI	5.23	2.64**
SocialClassZ	-0.4	2.74
EconWork	[REF]	
EconLk1stJob	-9.89	20.7
EconUnemp	-8.96	6.59
EconStudent	9.80	8.02
EconHome	-13.6	4.71***
EconRetired	-11.9	5.53**
EconDisabled	-29.3	5.07***
EconOther	-7.69	9.21
AccHouse	[REF]	
AccFlat	2.01	1.63
AccBedsit	27.3	7.18***
AccOther	8.78	7.93
AccNS	-4.82	7.92
Age0-14	-7.42	5.36
Age15-24	-15.0	8.35*
Age25-44	[REF]	
Age45-64	11.2	3.78***
Age65+	14.0	5.74**
IndAgric	-6.13	3.72*
IndBuilding	-9.82	3.28***
IndManufac	-21.5	3.22***
IndCommerce	[REF]	
IndTransComms	-0.136	6.51
IndPublic	-8.97	5.13*
IndProfess	-11.7	3.19***
IndOther	-9.98	3.43***
CompSingle	-7.68	2.94***
CompCouple	-8.27	3.49**
CompSingle&k	10.9	4.01***
CompCouple&k	[REF]	
CompOthFam	4.92	4.7
CompOtherNR	0.0461	4.34
EduNone	17.7	8.18**
EduPrimary	10.2	2.46***
EduLwrSec	-1.27	3.07
EduHighrSec	[REF]	
EduDegree	3.22	4.99
EduPostgrad	-4.43	6.62
EduNS	9.09	4.03**
IrishSpeakers	2.86	1.38**
ForeignBorn	8.13	2.16***
PersStillEducat	-2.78	8.07
HomeWorkers	-17.1	5.52***
Ln(AvgIncome)	18.8	1.92***
ExchangeSize	0.00145	0.000074***
ExchangeSize^2	-3.34E-08	2.51E-09***
Constant	-169	19.9***

Note: *, ** and *** denote significant at the 10%, 5% and 1% level respectively. Data sources: see Table 1 above.

Table 5: Second stage regression: dependent variable is *BroadbandShare*; 3388 observations

Variables	Coef.	Robust S.E.
AvgTimeSinceADSLhat	0.0605	0.00999***
AvgTimeSinceADSLhat^2	-0.00837	0.00221***
Ln(ExchangeDist)	-0.0265	0.00309***
PCOwnerYes	[REF]	
PCOwnerNo	-0.467	0.0363***
PCOwnerNS	-0.508	0.0999***
SocialClassABC	[REF]	
SocialClassD	0.0875	0.0584
SocialClassEF	-0.116	0.0524**
SocialClassGJ	-0.234	0.0564***
SocialClassHI	-0.0461	0.0451
SocialClassZ	0.0742	0.0421*
EconWork	[REF]	
EconLk1stJob	0.714	0.314**
EconUnemp	0.0985	0.0789
EconStudent	-0.155	0.0994
EconHome	0.0573	0.0736
EconRetired	-0.109	0.0842
EconDisabled	-0.0557	0.0885
EconOther	0.0349	0.106
AccHouse	[REF]	
AccFlat	-0.058	0.0237**
AccBedsit	-0.700	0.111***
AccOther	-0.296	0.115***
AccNS	-0.0716	0.097
Age0-14	0.0263	0.0778
Age15-24	0.105	0.117
Age25-44	[REF]	
Age45-64	0.179	0.0585***
Age65+	0.140	0.0871
IndAgric	-0.0835	0.0551
IndBuilding	-0.132	0.0483***
IndManufac	-0.0985	0.0526*
IndCommerce	[REF]	
IndTransComms	-0.145	0.0797*
IndPublic	-0.229	0.0712***
IndProfess	-0.377	0.0508***
IndOther	-0.285	0.0448***
CompSingle	0.0826	0.0402**
CompCouple	-0.00189	0.0468
CompSingle&k	0.221	0.0592***
CompCouple&k	[REF]	
CompOthFam	0.166	0.0681**
CompOtherNR	0.107	0.0589*
EduNone	0.0956	0.126
EduPrimary	0.140	0.0393***
EduLwrSec	-0.128	0.0464***
EduHighrSec	[REF]	
EduDegree	0.266	0.0807***
EduPostgrad	0.204	0.109*
EduNS	0.0928	0.0477*
IrishSpeakers	0.0557	0.0217***

Note: *, ** and *** denote significant at the 10%, 5% and 1% level respectively. Data sources: see Table 1 above.

ForeignBorn	0.0301	0.0301
PersStillEducat	0.209	0.11*
HomeWorkers	-0.234	0.0762***
Ln(AvgIncome)	0.179	0.0316***
Constant	-1.26	0.319***

Table 6: Summary of main results concerning socioeconomic influences on broadband demand and supply (+ positive effect, **–** negative, blank insignificant)

Influences	Demand	Supply
Distance to exchange (proxy for lower quality of service)	–	–
Higher disposable income	+	+
PC ownership	+	
Higher occupational/social class	+	+
Living in a house rather than other sorts of accommodation	+	
Commercial sector employment	+	+
Highest education level lower secondary	–	–
Share of population aged 45-64	+	+
Couples with children relative to other family types	–	+/–
Home workers	–	–
Foreign born persons		+
Residential addresses per exchange (and squared term)	*not included*	+ and – respectively

Source: analysis of Tables 3, 4, and 5 above.