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Broadband deployment in the United States is expanding rapidly but unevenly. Using new FCC census data on wireline and wireless broadband providers, we study mobile broadband provision within the United States. Although rural areas lag non-rural areas in the availability of residential access to both mobile and fixed broadband, mobile broadband is at least partially filling in geographical gaps in fixed-line broadband coverage. Multiple regression results indicate that population density and growth, and the fraction of blacks, Hispanics, and youth in an area are positive predictors of the number of mobile broadband providers. The fraction of Native Americans, Asians, and senior citizens in an area are negative predictors. Income is positively associated with the number of providers, with largest effects in rural areas. Finally, even after controlling for population density and income, rural areas continue to be associated with a lower number of providers.

INTRODUCTION

One of the valuable aspects of mobile communications service is the provision of broadband access to the Internet. Wireless mobile broadband deployment and usage are growing rapidly (FCC, 2010b). At the beginning of 2011, there were more than half a billion mobile broadband subscriptions worldwide, and that figure is expected to reach one billion by the end of the year (Ericsson, 2011). Nearly all consumers in the US have the option of subscribing to 3G mobile broadband networks, and next generation technologies such as LTE and WiMAX are available in many areas and being rolled out in most others.[1] As is typical with diffusion of technology, mobile broadband availability and its adoption by users are proceeding unevenly across geography, income levels, and among minority groups. This chapter examines the latest available data regarding the deployment of mobile broadband services in the US. The data provide a snapshot of mobile broadband availability at a fine level of geographic detail, permitting an examination of how mobile broadband deployment relates to area characteristics.

The key data for the empirical study come from the US Federal Communications Commission's (FCC) census of all broadband providers in the US as of June 2010. The data are the number of facilities-based carriers offering mobile high-speed connections within each Census tract. To augment the dataset, we add tract characteristics such as the population density, rural or non-rural location, racial and age diversity, and the income profile. We analyze the data with explorations of bivariate relationships and multiple regression analysis. For the latter, we develop a novel maximum likelihood estimation method for censored count data.

We explore three specific questions regarding the economic and demographic aspects of mobile broadband availability. First, to what extent are rural areas in the US lagging urban areas in deployment? Second, what is the role of mobile broadband in filling the geographical gaps left by fixed-line broadband deployment? Finally, how do the sociodemographic characteristics of the area affect the expected number of mobile broadband providers?

The analysis reveals that although rural areas lag non-rural areas in the availability of residential access to both mobile and fixed broadband, mobile broadband is at least partially filling in geographical gaps in fixed-line broadband coverage. The regression results indicate that holding other factors constant, population density and growth, and the fraction of blacks, Hispanics, and youth in an area are positive predictors of the number of mobile broadband providers. The fraction of Native Americans, Asians, and senior citizens in an area are negative predictors. Income is positively associated with the number of providers, with largest effects in rural areas, although the magnitude of its impact varies across the income distribution. Finally, rural areas are associated with a lower number of providers, even after controlling for population density and income.

[1] Per Wallsten and Mallahan (2010, p.7), "[a]bout 98% of the population lives in census tracts with 3G coverage, including about 77% of the population that can choose from three or more mobile 3G providers." Their estimates are likely to be highly accurate, since they make use of the industry-standard proprietary database on mobile service coverage (American Roamer).

BACKGROUND

Before describing and analyzing the data, we begin with a brief discussion of mobile broadband technology, covering the definition of "broadband," wireless network architecture, and types of mobile broadband service providers. In the second part of this section, we review the existing literature on the determinants of broadband provision in the US.

Mobile Broadband Technology

There is no universally accepted definition of mobile broadband. Loosely speaking, broadband refers to "high speed" data transmission, but there are various thresholds in use to define what broadband is. Until 2008, the FCC deemed any network speed of more than 200 kbps at least one way as broadband for purposes of its data collection on availability. With this low threshold, 3G and 4G mobile technology standards—HSPA, EVDO, LTE, and WiMAX in the US—qualify as broadband. By this definition, there were over 50 million mobile broadband subscribers in the US (FCC, 2011a) at the beginning of 2010, and over 70 million half a year later (FCC, 2011b). In 2008, the FCC revised its process for collecting data on broadband availability and began in addition to report residential subscription rates (but not availability) based on a higher threshold: 768 kbps downstream and 200 kbps upstream. The new threshold is also used by the US National Telecommunications and Information Administration (NTIA) and the Department of Agriculture's Rural Utilities Service (RUS) for various federal programs. In June 2009, the FCC began reporting the number of fixed broadband providers meeting a standard of at least 3 mbps downstream and 768 kbps upstream. In its *Sixth Broadband Deployment Report* in 2010, the FCC adopted a standard of 4 Mbps for download and 1 Mbps for purposes of its analysis, based on the claim that it is the "minimum speed required to stream a high-quality —even if not high-definition—video while leaving sufficient bandwidth for basic web browsing and e-mail" (FCC, 2010b, p.4). This standard is also the policy goal adopted in the National Broadband Plan as a near-term national broadband availability target for every household (FCC, 2010a).

To understand why mobile broadband is not universally available, it is instructive to take a (necessarily high-level) look at wireless network architecture. Starting with the end user, mobile broadband begins with a cell phone or smartphone, a laptop computer with a wireless broadband card or USB dongle, or other mobile Internet device. Such devices receive and transmit data using radio spectrum that the FCC licenses to carriers for mobile communications. Depending on the technology, the spectrum used may be shared between voice and data (as with the older EVDO, EDGE, and HSPA standards) or dedicated solely to data (as with the newer LTE and WiMAX standards). In the latter case, voice communication is digitized and treated like other data, using VoIP. Communication from the end user's device, called the "mobile station", is received by the service provider's access network, the first component of which is a base transceiver station (BTS), which contains antennas and radio systems for transmitting and receiving. The BTS sends the data on to its associated base station controller (BSC), perhaps via another BTS. In the latest technologies like LTE, the BSC (each of which communicates with many BTS's) connects directly to the service provider's IP routers to interface with the Internet.[2] Relatively early in the path from the end user to the Internet, typically between the BTS and the BSC, the data transmission switches from wireless to landline connections, although

[2] In earlier standards such as CDMA2000 that were not "all IP" networks, the BTS communicates with a radio network controller, which then sends the data on to a packet data serving node (PDSN). The PDSN then converts the data to IP and sends them to the service provider's router for access to the Internet.

communication between the BTS and BSC may also be accomplished by fixed wireless (microwave point-to-point) transmission systems. Thus, although many end users do not realize it, the wireless broadband network is largely made up of wired network infrastructure after the so called "last mile" (which is the first mile from the end user's perspective).

The spectrum licenses are a key input to the provision of mobile broadband. Under US law, the federal government owns the electromagnetic spectrum by fiat, and the FCC licenses its use for various purposes, including mobile broadband. The FCC first auctioned spectrum specifically for 3G mobile broadband use in 2006. However, given the flexibility attached to the use of certain spectrum licenses granted before that time, Verizon was able to begin offering mobile broadband service in 2003 (Berkman Center, 2010). In theory, the FCC has licensed enough spectrum in appropriate bands so that mobile broadband could be offered by multiple providers in any area of the US. Practically speaking, however, some of the licenses in any given area may be held by carriers delaying the transition to 4G technology or (less likely) choosing not to deploy mobile broadband at all. For example, in its bid to convince regulators to approve its acquisition of T-Mobile USA, AT&T has stated that transferring T-Mobile's spectrum licenses to AT&T would enable the company to offer LTE coverage to an additional 17% of the US population (AT&T *et al.*, 2011). The company's calculations are based on the fact that T-Mobile has no current plans to deploy LTE or other latest-generation technology.

The nature of the network architecture implies that densely settled urban areas are less costly to serve than are low-density rural areas. For example, for the cost of building an antenna, more potential customers can be reached in denser areas. Economies of scale can also arise from other elements in the network. For example, a single physical location for a BSC can serve more BTS's in urban areas, each mile of fiber optic line for transmission in the backhaul segment of the network can be more fully utilized in urban areas, and so on. Thus, approximately speaking, "low density" and "high cost" are viewed as synonymous when considering regulatory issues such as universal service support payments to carriers in rural areas. With a range of population density and resulting network costs in the US, it is natural that not all areas have the same number—or even any—mobile broadband service providers.

However, congestion can occur on wireless networks, since the traffic handled by a BTS is limited first by the electronic communications equipment installed and ultimately by the available spectrum. Additional equipment must be installed and service areas must be split by installing new BTS's as traffic grows (Gabel and Kennet, 1997). In wireless networks generally, as the site density increases, the variable costs for operations and transmission begin to dominate the fixed costs for radio equipment and the site (Johansson *et al*., 2004). Thus wireless architecture economies of scale may be largely exhausted at relatively low scales, compared to fixed networks. This implies that economies of scale for mobile broadband are perhaps most important in very low density areas, where the capacity of even a minimal wireless deployment is not fully utilized. The differing cost structures of fixed and wireless networks may also imply that mobile broadband is more cost effective to deploy in some rural areas than fixed alternatives, leaving open the possibility that mobile technology can be used to fill in broadband access gaps. Already with 3G technology, a solid business case could be made for wireless over wired broadband deployment in rural areas (Hörndahl, 2007).

There are three main types of mobile broadband service providers: mobile network operators (MNO's), mobile virtual network operators (MVNO's), and resellers. MNO's hold spectrum licenses and deploy wireless network infrastructure. The national wireless providers in the US (AT&T, Verizon, Sprint Nextel, etc.) are examples of MNO's. MVNO's do not own their own spectrum licenses and have wired communications network infrastructure, but not wireless infrastructure. Thus, to offer service to end users, an MVNO must contract with an MNO and make use of the MNO's wireless network to get the data traffic onto their own network. Some large cable companies (Cox, Comcast) operate mobile communications businesses as MVNO's. Resellers have neither spectrum licenses nor communications networks of their own, although they may handle their own customer service and billing. From the descriptions, it is clear that the question of mobile broadband availability hinges on the deployment decisions of the MNO's. These are the carriers covered in the FCC data examined below.

Previous Literature on Broadband Availability

Much scholarly inquiry has already been conducted on the question of broadband availability and the supply side of the digital divide in the US. Until recently, most work in this area focused mainly on the deployment of wired broadband networks. The willingness of a firm to deploy network resources in a local area is driven by economic and regulatory considerations. Demand factors such as the size of the local market, average income in the area, and other demographic characteristics such as the education and age profile of the area have all been shown to affect broadband penetration (Prieger, 2003; Flamm and Chaudhuri, 2007; Prieger and Hu, 2008b).[3] The same studies show that cost factors such as population density and the fixed costs of deployment, which are affected by the terrain, etc., also influence broadband penetration. Due to low population density and generally rougher topography than urban areas, rural areas are less likely to have broadband available at all, or more likely to be served only with lower-speed broadband or by few providers (Stenberg *et al.*, 2009; Li *et al*., 2011). Prospective and actual competition among providers, both intra- and intermodal also affects the incentives to enter the local broadband markets (Denni and Gruber, 2006; Prieger and Hu, 2008a; Wallsten and Mallahan, 2010). Regulatory policy toward broadband, such as mandated unbundling of network elements for use by competitors, can also impact the deployment decision by altering the expected return on network investment (Prieger and Lee, 2008).

Our second research question regarding the role of mobile broadband in filling remaining fixed broadband coverage gaps relates to the question of substitution between fixed and mobile broadband. Fixed and mobile substitution for broadband is only beginning to be explored as mobile broadband diffuses and data become available. A recent review article found virtually no published empirical work on the subject (Vogelsang, 2010), apart from one cross-country study indicating that through 2007 fixed and mobile broadband were complements rather than substitutes at the national level (see also Lee *et al*., forthcoming).

Examining where mobile broadband is making high-speed Internet access available where fixed connection are lacking or, less drastically, in areas relatively underserved by fixed connections, was not possible in the past with earlier FCC data. Until 2008, the FCC did not break down the mode of provision—fixed versus mobile—in its (then ZIP-code level) data. Thus, this chapter is

[3] See also the review of broadband demand studies in Hauge and Prieger (2010).

one of the first nationwide studies of mobile broadband provision for the US with any data. This chapter is perhaps closest to the work of Wallsten and Mallahan (2010), who analyzed the December 2008 wave of the FCC data with regression models. However, unlike the present work, they focus almost exclusively on wireline broadband providers.

EXPLORATION OF THE DATA

This section has three parts. We first describe the broadband and other data used in the analysis. Then, we examine the data with univariate and bivariate descriptive methods, to provide the big picture of mobile broadband deployment in the US. Finally, we perform multiple regression analyses to determine which characteristics of areas are associated with a higher number of mobile broadband providers, after controlling for other observed (and some unobserved) characteristics.

Description of the Data

The data on broadband provision are from the FCC Form 477 filings, which are a semi-annual census of all broadband providers in the US.[4] Data from the June 2010 wave of the Form 477 yield several variables of interest, all observed at the level of the Census tract.[5] The primary variable is the number of mobile high-speed providers offering service in the tract of at least 200 kbps one way. A provider is included if its service area includes any part of the tract; the entire tract need not be covered and the provider need not have any current customers in the area. A unique feature of the data is that the counts are interval censored: counts one to three are grouped in a single category. Other variables from Form 477 include the number of fixed high-speed residential connections per 1,000 households, according to the NTIA's definition of broadband (at least 768 kbps downstream and 200 kbps upstream). Fixed connections include DSL, cable modem, fiber, satellite, fixed wireless, PowerLine, and other wireline technologies such as T-3 dedicated access lines. Also available are two variables counting the number of residential fixed broadband providers in the tract. One uses the basic FCC definition of at least 200 kbps one way and the other uses a stricter definition of at least 3 mbps downstream and at least 768 kbps upstream. The FCC counts fixed broadband providers differently than mobile providers. To be counted, a fixed provider must have at least one subscriber in the tract. This difference affects the interpretation of broadband availability from fixed providers. For example, satellite service is available almost everywhere in the US, although there are probably many tracts with no subscribers to satellite broadband. The same is also true of fixed wireless service. Since the FCC requires all facilities-based broadband providers to file Form 477, the data we have are a complete census of the number of connections or providers, not just a survey.

We complement the FCC data with tract-level demographic data taken from GeoLytics *2010 Estimates*, allowing us to include commonly used predictors of broadband adoption such as population density, income, and race in our regressions. To classify each tract as rural or non-rural, data from the Economic Research Service (ERS) of the US Department of Agriculture are used. The ERS data categorize tracts based on population density, urbanization, and daily

[4] The detailed, company-specific data are confidential, but the FCC makes available certain data aggregated to the county and Census tract level, and we use the latter. The data are available from http://transition.fcc.gov/wcb/iatd/comp.html.

[5] Census tracts are composed of Census block groups, and are relatively small geographic areas. The median tract is about two square miles in area, although tracts can be much larger in rural areas.

commuting patterns.[6] The ERS data classifies 22.1% of Census tracts as "rural". Rural tracts cover 81.2% of the area of the US but only 19.5% of the population.

After a small number of tracts are excluded because either the demographic or FCC data are missing, the dataset for analysis contains 65,314 tracts with a population of 309.3 million. All fifty states and Washington, DC are included, but Puerto Rico and other US territories are excluded from the data. A few hundred additional observations must be dropped from the sample in the regressions because the demographic variables are not defined in tracts with no population or households. Summary statistics of the data can be found in Table 1. Both population-weighted and unweighted means are calculated. The weighted statistics are applicable to the descriptive empirical analysis, and the latter are applicable to the regression analysis (which is unweighted). The differences in weighted and unweighted means are generally smaller than 5% except for the rural indicator, population growth, and some of the race and ethnicity variables.

Descriptive Empirical Work

We begin the analysis of mobile broadband deployment by evaluating the distribution of mobile wireless connections over 200 kbps in at least one direction (the basic FCC definition of broadband). The figures in Table 2 are from the FCC (2011b); the publicly available data we use here does not contain this level of detail on transmission speed. The majority of mobile connections considered "broadband" have speeds between 200 kbps and 3 mbps. Only 7.8% of mobile broadband connections feature downstream speeds greater than 3 mbps, and 14.6% feature upstream speeds of greater than 768 kbps.

Our first research question asks to what extent rural areas are lagging behind urban areas in broadband deployment. We begin with a brief examination of fixed broadband provision and underserved areas. We define a population to be "underserved" by fixed broadband providers if either a) no more than 40% of households subscribe to fixed broadband service with 768 kbps download and 200 kbps upload or b) there are no fixed residential providers offering at least 3 mbps download and 768 kbps upload. A population is considered "severely underserved" if no more than 20% of households are subscribed to fixed broadband service offering 768 kbps download and 200 kbps upload. While these definitions admit the possibility that broadband is available but not desired in underserved areas, given the national household subscription rate of over 64% at the time, such areas most likely do not have adequate options.[7] Our results show that 50.1% of rural populations are underserved, compared to 24.6% of non-rural populations. The relative difference is even more apparent with severely underserved populations. An estimated 15.9% of rural populations are severely underserved as opposed to 5.1% of non-rural populations. Thus, while a rural resident is twice as likely as his urban counterpart to be

[6] A tract is considered rural if it has a Rural/Urban Commuting Area code in the range 4-10 (based on the 2000 Census), which is a standard definition of "rural" for many federal programs. See http://www.ers.usda.gov/Briefing/rurality/RuralUrbanCommutingAreas/.

[7] Per the FCC (2010b, Table 16), the household broadband subscription rate was 64% in June 2010, without including mobile broadband options. We cannot define underserved areas solely with respect to the presence of providers in the tract, because not all areas within the tract are guaranteed to be covered. Thus a tract listed as having four providers may have fewer than four—or even none at all—available at any particular household location.

underserved by fixed broadband in the US, he is more than three times as likely to be severely underserved.

Next, we look at the number of mobile broadband providers available to rural and non-rural populations, shown in Figure 1. As with the rest of the statistics in this subsection, the figures are weighted by population to estimate the proportion of people with access to broadband providers. Given that coverage everywhere within the tract is not guaranteed, the calculations of population with access to mobile broadband here will be at least slightly overestimated. Only a tiny portion of each population lacks access to any mobile broadband (0.1% of the non-rural population and 2.4% of the rural population). However, within rural populations, only 20.7% of people have access to four or more mobile broadband providers. Yet, 85.5% of non-rural populations have access to four or more providers. The results indicate that there is still a significant difference in the level of mobile broadband availability between rural and non-rural populations in the US.

Figure 2 is a graphical display of the number of mobile broadband providers in the US, with hatching to show rural areas. Darker areas correspond to a greater number of providers in the area. The map shows that most of the geographic areas of the nation have one to three mobile broadband providers. There are a large number of mobile providers in some major metropolitan areas like Chicago and Houston, and even in some smaller cities such as Columbus, Ohio, and Raleigh, North Carolina. Yet, there are relatively fewer choices in some major metropolises such as New York City, Los Angeles, and the San Francisco bay area. With some exceptions such as the California Central Valley, rural areas appear to have almost uniformly lower coverage than urban areas, in accord with the statistics in Figure 1. Given that Figure 1 is population weighted, the rural/urban disparities apparent in Figure 1 appear even starker in the map in Figure 2.

Our second research question asks what role mobile broadband plays in filling in geographical gaps left by fixed-line broadband deployment. Since the definition of being "underserved" concerns only fixed residential broadband service, mobile broadband providers may be offering service in underserved areas to supplement or replace fixed options.[8] To evaluate this possibility, we look at the number of fixed residential and mobile broadband providers in underserved and severely underserved areas. If mobile broadband is not filling in landline gaps, we would expect to see relatively similar distributions of mobile and residential broadband providers across areas.

Table 3 shows access to residential fixed and mobile broadband providers by underserved populations. Of the underserved population without access to any residential fixed-line high-speed providers offering advertised service of at least 3 mbps upstream and 768 kbps downstream, 95.3% have access to at least one mobile broadband provider. While the FCC data do not allow us to exclude mobile broadband providers offering relatively slow broadband from the calculation, the major wireless carriers in the US are deploying 4G technology in most of their service areas.[9] Thus, even if some of the mobile providers counted in Table 3 do not

[8] The FCC data do not include local subscription rates to mobile broadband service, and so we cannot define variables marking areas that are underserved with mobile broadband.

[9] Verizon Wireless has stated it will deploy LTE to its entire service area. AT&T has stated it will deploy LTE to about 98% of the population if its pending acquisition of T-Mobile USA is approved (and 80% if not). Sprint Nextel is deploying WiMax in many areas, but it has not announced its complete plans for 4G coverage as of mid 2011. T-

currently offer speeds meeting the threshold for the fixed providers, most of them expect to in the near future. The data thus indicate that mobile providers can play a significant role in extending broadband service to areas underserved by fixed broadband.

Figures 3 and 4 display the disparity in access to fixed versus mobile broadband providers among underserved and severely underserved populations (using the same speed thresholds as in Table 3). The data show that in almost all areas underserved by fixed broadband sources, more mobile broadband providers than higher-speed fixed broadband providers are offering service. Most underserved areas have only one to three fixed broadband providers, and given the low subscription rates in underserved areas it is likely that these providers do not cover the entire tract. However, 28% of the underserved population lives in tracts with four mobile providers, and about a third live in areas with five or more. For severely underserved areas, 10% of the population does not have any fixed broadband options at all, whereas only 2.3% lack access to any mobile provider. Again, the results show how mobile broadband appears to be filling in coverage gaps left by fixed broadband.

Multivariate Exploration of the Data

In this section, a multiple regression model is used to explore multivariate relationships between the number of mobile broadband providers serving the area (the dependent variable) and the area's demographic and economic characteristics (the regressors). The variables included as tract-specific regressors are a binary indicator variable for whether the Census tract is rural, population density (inhabitants per square mile, in logs), median household income (in logs), the number of households, annualized population growth since 2000, the fraction of the population in various racial and ethnic categories, and the fraction of the population that is young (under 20 years) and older (65+ years). Summary statistics for these variables are in Table 1. These variables are chosen because previous literature has generally found them to be important for predicting where broadband is offered in the US (Prieger, 2003; Prieger and Lee, 2008; Prieger and Hu, 2008a; Wallsten and Mallahan, 2010). In the final regression, variables for the total number of fixed broadband providers (basic definition: 200 kbps one way; in logs) and the fraction of those that meet a higher standard of 768 kbps one way are added.

The standard regression model when the dependent variable is a count is Poisson regression (Cameron and Trivedi, 1998). Due to the grouping of one to three providers in the FCC data, we cannot use standard Poisson regression. Instead, we develop a novel maximum likelihood estimation (MLE) method that accounts for the interval censored data.[10] Technical details of the estimation technique are in an appendix. Given that the estimations are for areas instead of people, they are unweighted.[11] In the Poisson model, the natural log of the expected number of mobile broadband providers in a tract (y_i), conditional on the regressors, is a linear function of the regressors:

Mobile has deployed HSPA+ throughout its service area but has no plans to deploy LTE or WiMax. Most of the population in the US has access to at least one of these carriers.

[10] Although there is a small literature on the closely related question of estimation with interval-censored counting process data, our work is the first example of an applied statistical model for interval-censored count data (where the censoring depends on the counts, not the observation times) that we can find in the econometric literature. Previous empirical studies for censored count data that we found dealt only with left or right censoring.

[11] Repeating Estimation 1 below with population weights did not change any of the signs of the coefficients or our qualitative conclusions.

$$\ln E(y_i|x_i) = \alpha_s + \beta' x_i$$

where the first term α_s is a state-specific intercept, β is a vector of coefficients, and x_i is the vector of regressors for Census tract i. The state-specific intercepts, or "fixed effects," are not parameters of interest in themselves, but are included to capture the effect of all unobserved factors that are common to all areas within a state (for example, the state regulatory climate or statewide economic factors). Including the state fixed effects implies that the regression estimates are identified only from within-state variation in the regressors. With our cross-sectional data, however, there is no way to eliminate the influence of tract-specific factors that are correlated with regressors and the dependent variable. For example, a particular area may be expected to enjoy strong employment growth in the near future, which could attract both people and broadband providers to the area. Because of the possibility of such unobserved factors and the non-experimental nature of the data, it is important to note that there is no causal interpretation of the results. Nevertheless, the regression uncovers relationships among the variables and helps to show which variables are most strongly associated with broadband provision.

The estimation results are in table 4, and we begin with examining Estimation 1 in the first two columns. Except as noted below, all the estimated coefficients are highly statistically significant. In the table, the coefficients are multiplied by 100. With this scaling, the semi-log specification of the model implies that the coefficient for demographic variable x_j can be interpreted as the percentage change in the number of providers resulting from a one-unit change in x_j. For example, in the first estimation, the coefficient on the indicator variable *rural* of -43.1 means that other factors held constant, the average number of mobile broadband providers is 43.1% lower in rural areas than in non-rural areas. This result is particularly interesting, because the estimation holds constant population density and income, two factors often assumed to explain why rural locations have fewer broadband providers. Perhaps the large negative rural coefficient picks up the cumulative effect of being in a large area (not just the specific tract) with low income and density. That is, a non-rural tract may have low density because it includes a large urban park, but such an area is still likely to have urban-level coverage.

When the regressor is in logs, the reported estimate is an elasticity, showing the relationship between x and y in percentage terms. The second row, for example, shows that a 100% increase in population density is associated with 6.83% more providers, *ceteris paribus*. A positive association is expected, since areas with higher population density are cheaper to serve because of economies of scale, as described in the background section on mobile broadband technology above. While the coefficient appears to be small, there is a huge range of population density in the US. To interpret the magnitude of the effect of density, consider a change from the 25th percentile density (260 persons/sq. mile (*ppsm*)) to the 75th percentile (5,580 ppsm). This 20-fold increase in density is associated with a 140% increase in the number of mobile broadband providers.

Income enters the regression specification through a four-part linear spline.[12] The spline allows the slope coefficient to differ among income groups. This flexibility in modeling the effect of income is necessary for a few reasons. For very low income areas, marginal increases in income may do little to attract broadband deployment until a certain threshold is met. Beyond that threshold, additional wealth in an area may attract more providers, up until a threshold on the high end, beyond which all providers wish to enter and even higher income provides no additional incentive. Our expectation, therefore, is that income will display an ogive (*S*-shaped) impact on broadband provision. The empirical results bear out the expectation. The threshold for the income groups are chosen to be the 5th, 25th, and 50th percentiles of the household median income in the tracts across the nation. These thresholds correspond to incomes of $20,683, $31,574, and $40,876 per year. The coefficients show that for median income below the 5th percentile, there is no association between income and the number of providers (the coefficient is slightly negative, but statistically insignificant). For incomes in the range from the 5th percentile up to the first quartile, the income elasticity of broadband provision rises to 0.06 and turns highly significant.[13] The income elasticity, 0.28, is even larger in the range from the first quartile to the median. For income above the median, the strength of the effect falls to 0.09, as expected.

The ogive shape implied by the slope coefficients is depicted in graphical form in Figure 5. In the figure, the scale for the *x*-axis is log income, and to focus on the region in which most of the data lies the regression line is not shown for small incomes. The knots of the spline appear in the figure as the kinks in the piecewise linear regression function. The regression lines for rural and non-rural areas in Estimation 1 are parallel, with the vertical distance between them coming from the rural coefficient. That is, although the level of the regression line differs between rural and non-rural areas, the impact of increasing income (the regression slope) is the same in this specification.

The number of households is negatively associated with the number of providers. Given that the regression controls for population density, a larger number of households implies that the area is larger. By construction of the Census Bureau, tracts in rural areas are larger. Given the strongly negative impact of rural location discussed above, it is likely that the negative coefficient for the number of households also reflects the fact that rural locations have fewer providers. On the other hand, areas that have grown the most in the past decade have the most providers. The coefficient for the population growth rate implies that an additional 10 percentage points of growth is associated with 0.18 percent increase in mobile broadband providers.

Some studies show that race and ethnicity are correlated with fixed broadband deployment, but their apparent impacts often disappear once income, education, and other related demographic factors are controlled for (Prieger, 2003). The situation may differ with mobile broadband, which is a relatively more important means of Internet access for African Americans and Hispanics than for whites. Recent statistics indicate that minorities in the US are less likely to own computers but more likely to have mobile devices than are non-minorities. Gant *et al.* (2010) found that while over three-fifths of whites had a working desktop computer at home,

[12] A spline relaxes the assumption that the slope of $\ln E(y|x)$ is linear in x_{income}. Instead, the slope is piecewise linear, with three "kinks" at the thresholds defining the four income groups.
[13] Recall that the reported estimates in the table are multiplied by 100. An income elasticity of 0.06 implies that a 1% increase in income is associated with a 0.06% increase in the number of providers.

only about half of blacks and Hispanics did. Mobile phone ownership, on the other hand, is much more common than computer ownership among minorities. Gant *et al*. (2010) showed that blacks and Hispanics are about 30 percentage points more likely to own a cell phone than a computer. In fact, one recent survey showed that when it comes to smartphones, usage is higher among Hispanics (45%) and African Americans (33%) than among whites (27%) (Kellogg, 2011).[14] Minorities are not only more likely to have mobile Internet-capable devices, they are more likely than whites to use them to access the Internet. While only 30% of whites use their cell phone to access the Internet, half of all blacks and 42% of Hispanics do (Gant *et al*., 2010). To further underscore the importance of mobility for the broadband experience of minorities, note that African Americans are more than twice as likely as whites to say their cell phone is their preferred device to access the Internet, and Hispanics are 60% more likely to say so than whites are (Gant *et al*., 2010). Thus, assuming that deployment is greater in areas with higher expected demand, after controlling for income, we may expect mobile broadband to be more available in minority areas.

The variables for race included in the estimation are the fraction of people who identify themselves as black alone, Native American alone, Asian or Pacific Islander alone, or any combination of two or more races (multiracial). The excluded categorical variable is for white alone. The variable for ethnicity is the fraction of people that are Hispanic.[15] The coefficients for race and ethnicity are highly significant and positive for blacks, Hispanics, and multiracial persons. The estimate for blacks implies that (*ceteris paribus*) an all-black area is expected to have 10.8% more mobile broadband providers than an area with no African Americans. The similar calculation for Hispanic areas yields a figure of 6.8%. The coefficient for multiracial persons is particularly high (57.9). On the other hand, the estimate for Native Americans is negative. Fewer than half of Native American households subscribed to broadband of any form in 2010, the lowest subscription rate by far among any major racial or ethnic group (NTIA, 2011). Thus it is not surprising that Native American areas have fewer broadband providers, both because of lower expected demand and the remoteness of some of Indian Country in the US. Areas with more Asian/Pacific Islanders are also associated with fewer mobile providers, contrary to some previous research for fixed broadband provision (Prieger and Hu, 2008a).

Many surveys have shown that mobile and general Internet use declines monotonically with age in cross-sectional data (Gant *et al.*, 2010; Lenhart *et al.*, 2010).[16] The results show that areas with more inhabitants under 20 years of age have a higher expected number of providers (although the result is significant only at the 5% level). Exploratory investigation determined that the impact of the fraction of senior citizens in the area was non-monotonic. Up to the third quartile of the variable (the range from zero to 17.3% seniors in the area), increasing the fraction of seniors in the area decreases the expected number of mobile broadband providers, as expected.

[14] Smartphones were defined in the survey as mobile phones with "app-based, web-enabled operating systems." Among new purchasers of mobile phones, the differences in smartphone adoption among groups are even starker. Kellogg (2011) reports that "[a]lthough only 42 percent of Whites who purchased a mobile phone in the past six months chose a smartphone over a feature phone, 60 percent of Asians/Pacific Islanders, 56 percent of Hispanics, and 44 of African Americans who recently bought cellphones chose smartphones."

[15] Consistent with US Census Bureau methodology, a person of Hispanic ethnicity can be of any race. Thus there is double counting between, for example, the white category for race and Hispanic ethnicity category.

[16] That is, at any given time an older person is less likely to be an Internet user than a younger person in the US. The statement is not to be interpreted as saying that an individual is less likely to use the Internet as he ages.

However, the coefficient for the quarter of areas with the highest fraction of seniors is large and positive. Further investigation showed that these areas are likely to be in urban areas, and so the latter result is picking up an urban effect in part.

The fixed effects for the states are not shown in the table. The wide variation in the size of the state coefficients shows that mobile broadband provision varies greatly among states due to unobserved factors apart from the demographic variables for which the estimations control. The difference between the three smallest state fixed effects (for the rural states Montana, North Dakota, and South Dakota) and the three largest (for Oregon, Oklahoma, and Illinois) implies the latter are predicted to have 67% more mobile broadband providers than the former, holding other factors constant.[17]

Estimation 2 (also reported in Table 4) is identical to Estimation 1, except that the specification allows the impact of income to vary between rural and non-rural areas. With the rural indicator variable interacted with the income spline, the main set of coefficients on the income variables pertains to non-rural areas, and the coefficients on *rural* × *income* show the incremental change in the slope coefficients between rural and non-rural areas. The results regarding the impact of the other variables is similar to those in Estimation 1, and here we concentrate on the effect of income. The ogive form of the income effect found in Estimation 1 persists in Estimation 2 for non-rural areas. However, the slope of the expected number of broadband providers in income for rural areas is much larger. From the fifth percentile upward, the magnitude of the income coefficient is much larger in rural areas than in non-rural areas in the same income group. The net effects are depicted in Figure 5. In this case, the vertical distance between the regression lines for rural and non-rural areas stems from both a different intercept (coming from the rural coefficient) and the differing slopes. The figure reveals that the impact of income in rural areas is nearly as strong for the highest income group as in the next highest income group, so that the ogive form is only barely apparent for rural areas. Altogether, the results show that while the income of an area is a statistically significant predictor of the number of mobile broadband providers, the magnitude of the association (given by the slope of the regression line) is much larger in rural areas. Rural areas with the lowest median income are therefore most at risk to be underserved with mobile broadband, even after controlling for population density and the race and age profile of the areas.

In Estimation 3, reported in the final columns of Table 4, the variables pertaining to provision of fixed broadband are added. If mobile broadband is most likely to be offered where fixed broadband is already available, even after controlling for observable characteristics of the area that are related to demand and cost, then the coefficients on the new variables will be positive. If, holding other observable factors constant, competition from fixed broadband makes the area unprofitable for mobile broadband, then the coefficients will be negative. The estimation shows the former result: the number of fixed broadband providers is positively and significantly associated with the number of mobile broadband providers. The size of the effect, however, is not large. The coefficient implies that changing the number of fixed broadband providers from its median value (4) to its third quartile (5) increases the expected number of mobile providers by

[17] The latter states have a large number of providers in the Portland, Oklahoma City/Tulsa, and Chicago metropolitan areas, respectively.

only 1.0%. Similarly, the fraction of the fixed providers that offer higher speed broadband is also positively associated with mobile broadband provision.

The positive apparent impact of fixed on mobile providers can be explained by a few reasons. After controlling for the other variables in the estimation, a larger number of fixed providers may indicate the presence of unobserved factors that make the area more profitable in which to offer broadband service. There may also be a competition effect, as mobile providers seek to meet the competition in areas well served by fixed providers. Since many of the large mobile broadband providers such as AT&T and Verizon also offer wired broadband, there may also be economies of scope making it more cost effective to enter mobile markets in which the firm already operates as a fixed broadband provider. The estimated coefficient commingles these effects, and we caution again that no causal interpretation can be ascribed directly to the estimate.[18]

FUTURE RESEARCH DIRECTIONS

As mobile broadband penetration continues to increase in the US, three avenues of research are opening as more data becomes available: the link between mobile broadband deployment and economic development, the extent of substitution between fixed and mobile broadband, and the role mobile broadband plays in closing the Digital Divide. We touch briefly on these three research areas in turn.

Mobile broadband, as does fixed broadband, has tremendous potential to transform economic activity because it is a *general purpose technology* (GPT). Bresnahan and Trajtenberg (1995) characterize a GPT by its pervasiveness, potential for technical improvements, and potential to increase the productivity of R&D in downstream sectors. A GPT like broadband thus spreads throughout all aspects of the economy and creates productivity gains in many industries. In the case of Internet and broadband GPT, the technology directly raises productivity in industries that are intensive users of information and communications technology (ICT) (Varian *et al*., 2002). The beneficial effects of improved productivity and lower costs in industries that are heavy users of ICT ripple outward to other sectors of the economy that use these firms' outputs as inputs. Prieger and Heil (2010a,b) review the mechanisms by which the diffusion of ICT leads to general microeconomic and macroeconomic growth. There is a growing empirical literature indicating that the potential for broadband to stimulate economic development is real, although perhaps hard to quantify (Gillett *et al*., 2006; Crandall *et al*., 2007; Kolko, 2010; Mayo and Wallsten, 2011). Few studies have yet attempted to pin down the specific contribution of *mobile* broadband to economic development, and this question will become increasingly important as the mobility of broadband grows.[19]

What is the extent of broadband "cord cutting," and what role might it play in narrowing the Digital Divide? Fixed to mobile substitution has been studied for voice communication (Vogelsang, 2010), but (as mentioned above) we are aware of no empirical work yet on cord cutting in the broadband arena. Measurement of the extent to which consumers are willing to

[18] In econometric terms, the variables for fixed broadband provision are likely to be endogenous, preventing estimation with our method of the causal impact of increasing the number of fixed providers on the expected number of mobile providers. Given the descriptive nature of the exercise here, this is not a serious limitation for present purposes.
[19] See some of the studies in the Additional Reading section for preliminary work on the subject.

use mobile broadband instead of wired alternatives is important for policy issues such as universal service mechanisms and support payments.

Since statistics have first been available in the US, some minority groups have lagged whites in Internet and broadband adoption. A recent FCC survey (Horrigan, 2010) found broadband usage to be 69% for whites, 59% for African Americans, 49% for Hispanics. The trend appears to be at least somewhat promising, however, since in the CPS data the growth rate in broadband use for African Americans and Hispanics was higher in the most recent data than it was in the 2007 to 2009 period. A sizable body of empirical literature has explored reasons for lower broadband usage by minorities. Explanations proposed for the broadband gap include lack of computer ownership, low income, and (particularly in earlier years) lack of broadband availability (Prieger and Hu, 2008b).

Mobile broadband has a promising role to play in closing the broadband digital divide in the US between minorities and others. As discussed in the estimation section above, minorities are more likely than others to have mobile devices and are more likely to use them to access the Internet. In fact, minorities lead whites in using the full range of their smartphones' capabilities. African Americans and Hispanics are more likely than white cell phone owners to use their mobile device to text, use social networking sites, surf the Internet, email, play games, post multimedia content online, and even make charitable donations via text messaging (Smith, 2010). As a group, blacks are even more satisfied with their online experiences than others, indicating that African Americans do not feel that mobile broadband is inferior to fixed broadband. Gant *et al.* (2010) find that 65% of African American Internet users perceived that they are "very satisfied" with their broadband service, compared to 61% of Hispanics and 57% of whites. Continuing research into the evolving role that mobile broadband plays in connecting minorities to the Internet is warranted, especially as the consumption of video programming (for which mobile broadband is perhaps less well suited than fixed alternatives) grows on the Internet.

CONCLUSION

Before users can take advantage of the benefits of mobility in Internet access, it must be available where subscribers are. This chapter has addressed three issues regarding mobile broadband availability in the US: the rural/non-rural deployment gap, the ability of mobile broadband to close the gap, and the importance of various economic and demographic factors in predicting the number of mobile broadband providers in an area. Our exploration of data from the FCC show that deployment gaps between rural and other areas persist. A rural resident is twice as likely as his urban counterpart to be underserved by fixed broadband, and is more than three times as likely to be severely underserved. There is also a significant difference in the level of mobile broadband availability between rural and non-rural populations. Regarding the second issue, the data show that almost all of the underserved population lacking access to higher-speed fixed broadband has access to at least one mobile broadband provider. Thus, it appears that mobile providers can play a significant role in extending broadband service to areas underserved by fixed broadband. Exploration of the third issue indicates that population density, population growth, income, and the fraction of the population that is African American, multiracial or other race, Hispanic, or young are positively associated with the predicted number of service providers. Rural location and the fraction of the local area population that is Native American, Asian, or seniors are negatively associated with the predicted number of mobile broadband providers offering service. Thus, while mobile broadband appears to be an important contributor to the narrowing of the Digital Divide in the US, continued attention from policymakers is warranted to monitor broadband availability in rural areas and to certain population groups of interest.

APPENDIX

In Poisson regression, it is assumed that conditional on $\lambda = \exp(\beta' x)$, the data generating process for y follows a Poisson distribution, so that the probability density function (pdf) of y is:

$$f(y|\lambda) = \frac{\lambda^y \exp(-\lambda)}{y!}$$

When the data are interval censored, so that when y is in the interval [1,3] the exact count is not known, additional notation is required. Let c_i be a censoring indicator taking value 1 if observation i is censored and 0 if not. Then the likelihood function for the data (y_i, c_i) for an observation may be written as

$$L_i(\beta_i) = [f(y_i|\lambda_i)]^{(1-c_i)} \left[\sum_{k=1}^{3} f(k|\lambda_i)\right]^{c_i}$$

Note that when the observation is censored, the contribution to the likelihood is the probability that the count is 1, 2, or 3. The log likelihood function for all the data is found from taking the log of L_i and summing over all observations. MLE finds the coefficient estimates that maximize the log likelihood function. The estimates have the desirable statistical properties of consistency and efficiency. MLE was performed with a user-written program in Stata 11.2 (available upon request from the first author), and appears to be one of the first empirical applications of estimation with interval-censored count data in the literature.

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Tables

Table 1. Summary Statistics of the Data

	Weighted	Unweighted Statistics			
Variable	Mean	Mean	Standard Deviation	Minimum	Maximum
rural	0.195	0.220	0.42	0.00	1.00
population density (log)	7.205	7.049	2.22	-2.30	12.38
income (log)	10.68	10.63	0.44	0.00	12.22
# households (log)	7.623	7.309	0.91	-0.69	10.03
population growth	0.155	0.078	0.24	-0.85	6.00
race, % black	0.129	0.145	0.24	0.00	1.00
race, % native american	0.009	0.010	0.05	0.00	1.00
race, % asian	0.048	0.043	0.08	0.00	1.00
race, % other	0.017	0.016	0.02	0.00	0.67
ethnicity, % hispanic	0.161	0.139	0.20	0.00	1.00
youth, %	0.267	0.261	0.05	0.00	1.00
seniors, %	0.136	0.145	0.06	0.00	1.00
# fixed BB residential providers (log)	1.201	1.152	0.47	-0.69	1.95
fixed BB residential providers, % > 3 mbps up/768 kbps down	0.550	0.575	0.40	0.00	1.00

Notes: First column has averages weighted by population (as used in the descriptive empirical work). Statistics in the remaining columns are unweighted (as used in the regression analysis).

Table 2. Mobile Wireless Connections over 2000 kbps in at Least One Direction, July 2010.

	Downstream speed			
Upstream speed	*200 kbps - 3 mbps*	*3-6 mbps*	*6+ mbps*	*total*
200-768 kbps	85.2%	0.2%	0.0%	85.4%
768 kbps - 1.5 mbps	6.9%	0.6%	1.4%	8.9%
1.5+ mbps	0.2%	1.4%	4.0%	5.7%
total	92.3%	2.3%	5.5%	100.0%

Note: total number of connections is 71.2 million. Source: FCC (2011b)

Table 3. Residential and Mobile Broadband Providers for Underserved Populations, June 2010

Residential Broadband Providers (3+ mbps up/ 768+ kbps down)	**Mobile Broadband Providers (200+ kbps one way)** 0	1-3	4	5	6	7+	Total
0	4.7%	69.8%	12.8%	5.9%	6.6%	0.2%	100%
1-3	0.9%	33.6%	29.6%	20.4%	12.8%	2.7%	100%
4	0.0%	28.3%	24.3%	24.4%	21.5%	1.6%	100%
5	0.0%	29.6%	22.6%	39.5%	8.4%	0.0%	100%
6	0.0%	79.9%	0.0%	0.0%	20.1%	0.0%	100%
Total	1.2%	37.0%	27.9%	19.1%	12.4%	2.5%	100%

Notes: each cell is the percentage of mobile broadband providers within the row falling into the category given by the column heading. The figures are population weighted.

Table 4. Poisson Regression Analysis of the Number of Mobile Broadband Providers

	Estimation 1		*Estimation 2*		*Estimation 3*	
Y = # mobile broadband providers in Census tract	Coefficient (×100)	*P*-Value	Coefficient (×100)	*P*-Value	Coefficient (×100)	*P*-Value
rural	-43.05	0.000	-62.31	0.471	-57.50	0.504
population density (log)	6.83	0.000	6.81	0.000	6.67	0.000
income (log, [0, 5] %ile)	-1.03	0.222	-0.46	0.598	-0.98	0.262
income (log, [5, 25] %ile)	5.76	0.000	4.73	0.000	5.15	0.000
income (log, [25, 50] %ile)	28.41	0.000	20.68	0.000	20.52	0.000
income (log, [50, 100] %ile)	8.85	0.000	9.44	0.000	9.22	0.000
rural × income (log, [0, 5] %ile)			0.62	0.943	0.21	0.980
rural × income (log, [5, 25] %ile)			19.44	0.000	18.58	0.000
rural × income (log, [25, 50] %ile)			33.90	0.000	32.44	0.000
rural × income (log, [50,100] %ile)			38.15	0.000	38.41	0.000
# households (log)	-1.35	0.000	-1.24	0.000	-1.31	0.000
population growth	1.79	0.000	1.44	0.000	1.41	0.001
race, % black	10.78	0.000	9.82	0.000	9.86	0.000
race, % native american	-16.38	0.003	-11.71	0.033	-8.88	0.100
race, % asian	-9.10	0.000	-8.19	0.000	-8.29	0.000
race, % other	57.90	0.000	56.14	0.000	53.83	0.000
ethnicity, % hispanic	6.85	0.000	6.02	0.000	6.17	0.000
youth %	6.79	0.041	7.02	0.035	6.41	0.056
seniors % ([0, 75] %ile)	-10.10	0.003	-8.21	0.016	-8.53	0.012
seniors % ([75, 100] %ile)	25.63	0.000	23.19	0.000	22.59	0.000
# fixed BB residential providers (log)					4.10	0.000
fixed BB residential providers, % > 3 mbps up/768 kbps down					6.59	0.000
Wald Chi-Square stat (df)	99,944.34 (66)		100,667.12 (70)		101,363.45 (72)	
P-value of Chi-Square statistic	0.000		0.000		0.000	
Log Likelihood	-91,672.090		-91,607.051		-91,585.623	

Notes: sample size is 64,914 in all estimations. The unit of observation is a Census tract. Estimated standard errors used to calculate *p*-values are robust to heteroskedasticity. Coefficients for *x* denoted with *[a,b] %ile* pertain to the regression slope in the range $c \leq x \leq d$, where c is the a^{th} percentile and d is the b^{th} percentile of x.

Figures

Figure 1. Mobile Providers of Broadband by Rural and Non-Rural Population, June 2010

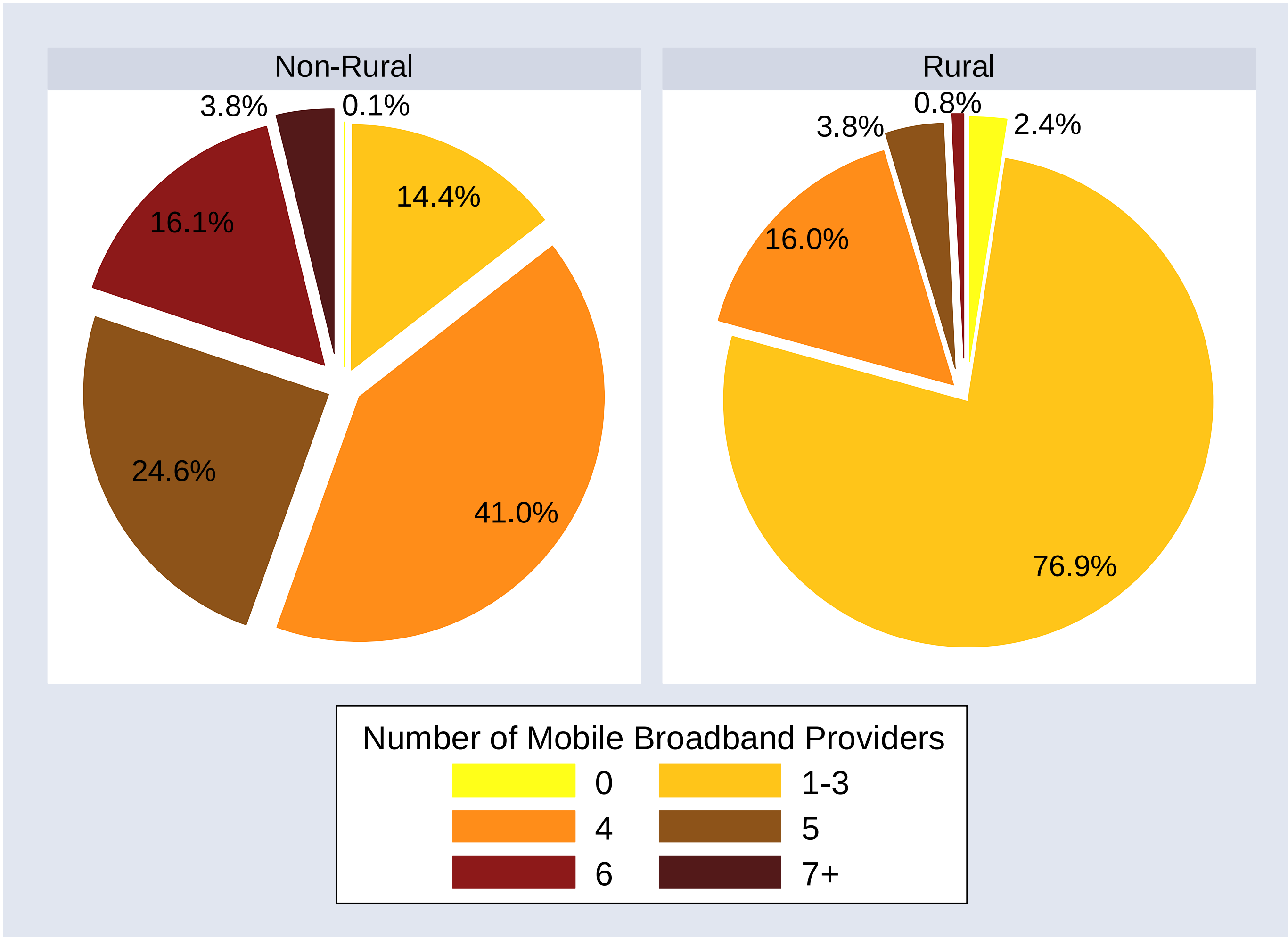

Figure 2. Mobile Providers of Broadband in the US, June 2010

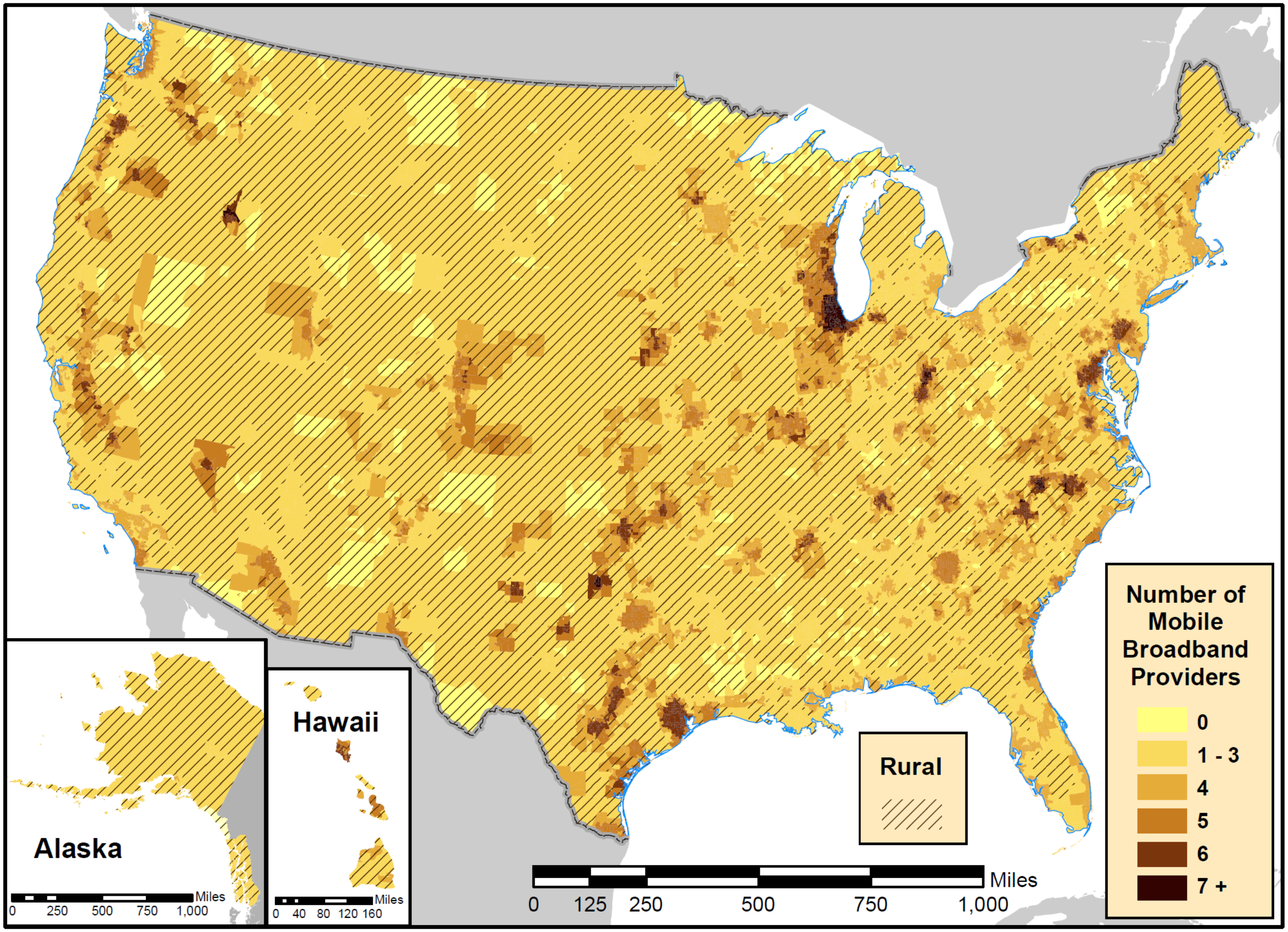

Figure 3. Residential Versus Mobile Broadband Providers for Underserved Populations, June 2010

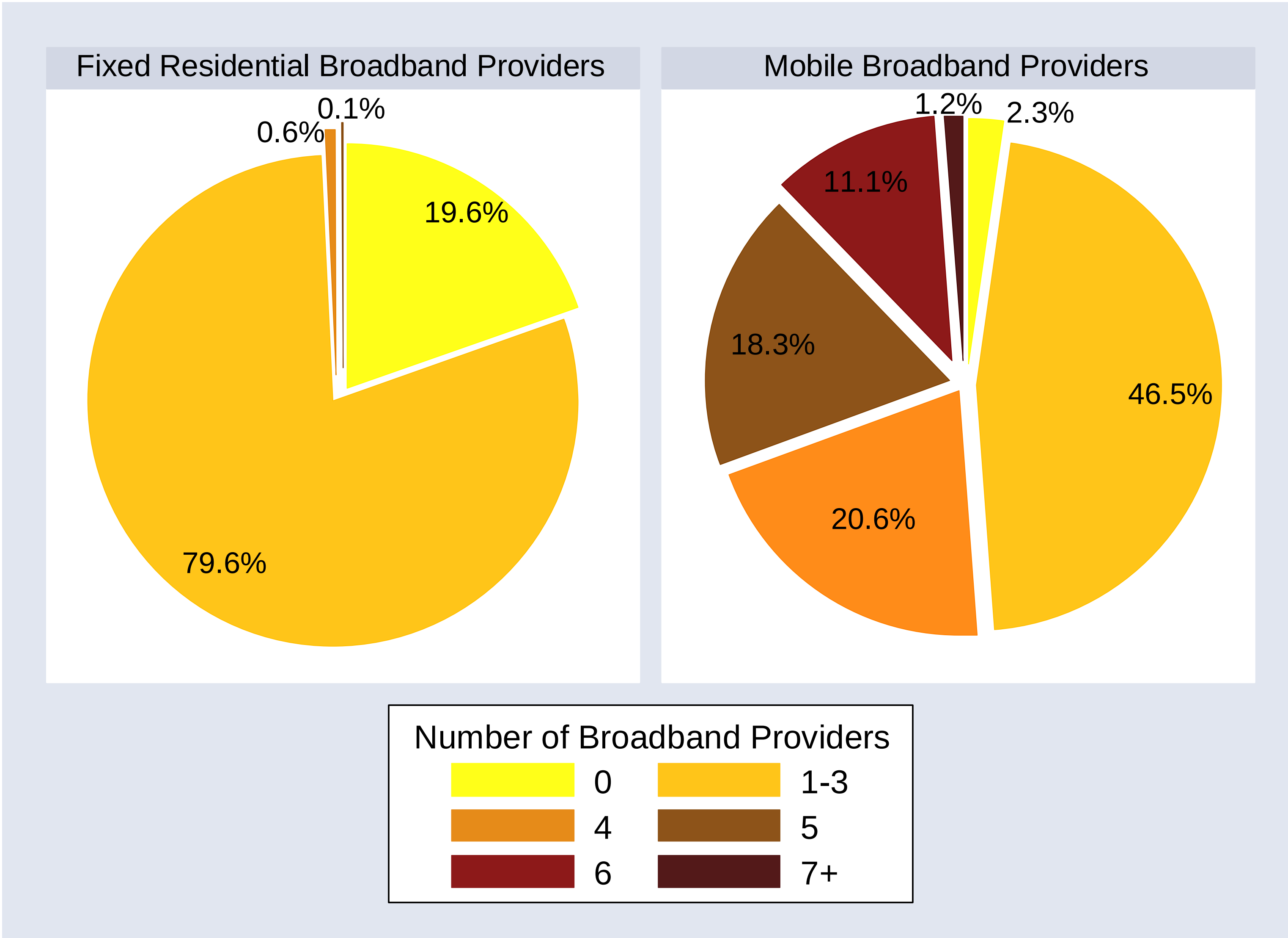

Figure 4. Residential Versus Mobile Broadband Providers for Severely Underserved Populations, June 2010

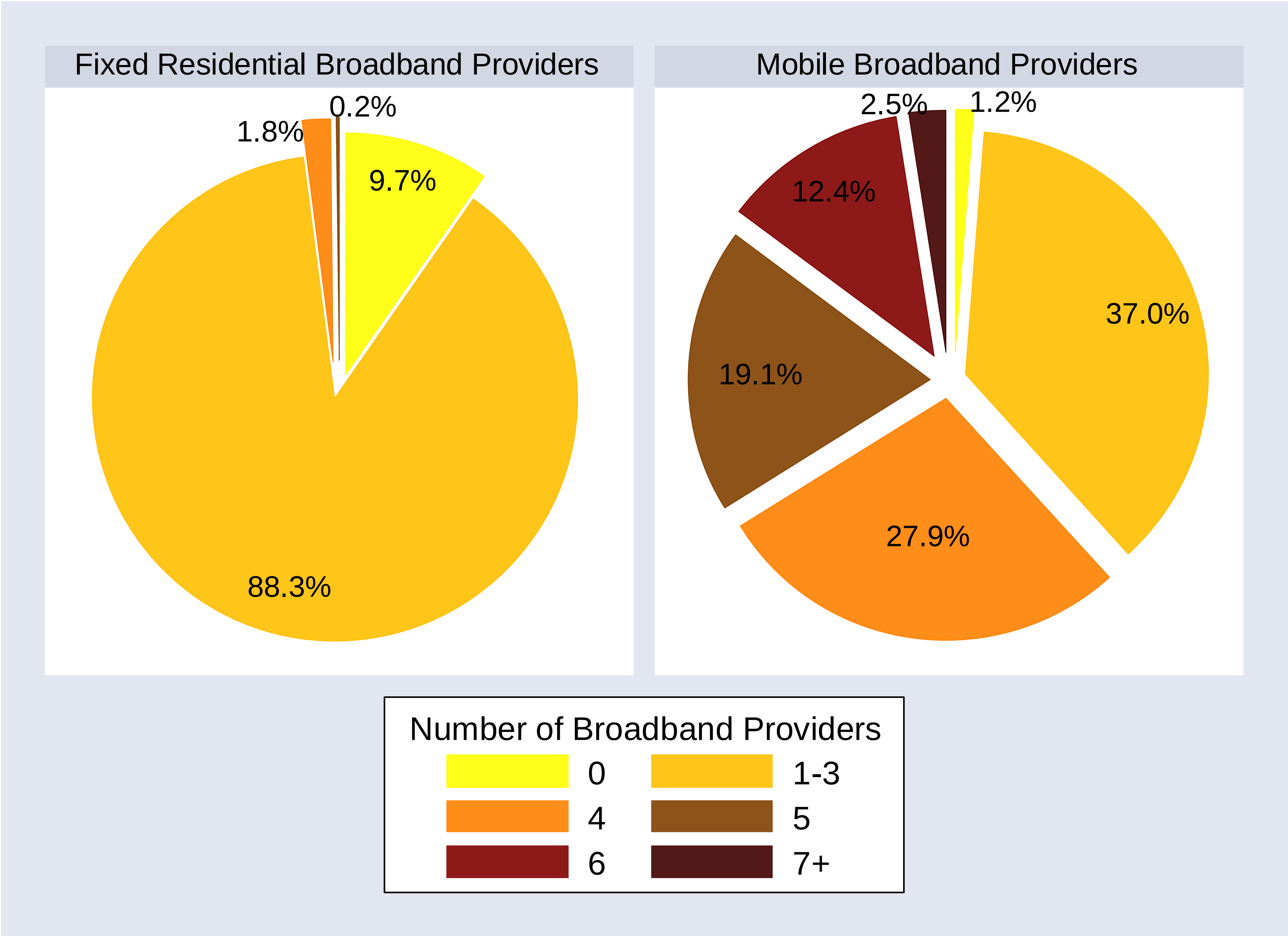

Figure 5. Partial Effect of Income on the Number of Mobile Broadband Providers