USTELECOM
THE BROADBAND ASSOCIATION

April 30, 2013

**<u>Ex Parte</u>**

Ms. Marlene Dortch
Secretary
Federal Communications Commission
445 12th Street, SW
Washington, D.C. 20554

Re: USTelecom Petition for Forbearance From Certain Legacy
Telecommunications Regulations, WC Docket 12-61

Dear Ms. Dortch:

On April 19, 2013, USTelecom submitted an ex parte in response to questions raised by Commission staff in connection with USTelecom's pending petition for forbearance.

One of the documents attached to the ex parte, "*Demand in a Portfolio-Choice Environment: The Evolution of Telecommunications"* by J. Macher, J. Mayo, O. Ukhaneva, G. Woroch (Aug. 2012), had certain pages inadvertently left out. We are now filing the document in its entirety to include the missing pages.

Pursuant to Commission rules, this ex parte letter is being filed in the above-referenced docket.

Sincerely,

Glenn Reynolds
Vice President, Policy

Attachment (1)
c: Lisa Gelb
Eric Ralph
Bill Dever
Claudia Pabo
Jenny Prime
Greg Kwan

# Demand in a Portfolio-Choice Environment: The Evolution of Telecommunications

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John W. Mayo*
Olga Ukhaneva*
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**Abstract**

We explore the pattern and evolution of the rapidly changing landscape of consumers' wired and wireless telecommunications choices with a model that extends the traditional (node-to-node) demand structure. We then empirically estimate a consumer choice model using household-level observations from 2003-2010. Households that are more affiliated with their domicile are more prone toward wireline services while more "on the go" households are more attracted to wireless telephony. The estimations indicate that subscription to wireline and wireless telephony are substitutes rather than complements. Finally, the quality convergence in wireless and wireline services has contributed significantly to shifts in consumers' telephone portfolios.

August 20, 2012

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[1]We acknowledge the helpful feedback of J. Bradford Jensen, Tom Lyon, Michael Katz, Carlos Martins-Filho, Julie Mortimer, Russell Pittman, Dennis Quinn, Scott Savage, Victor Stango, Francis Vella, Ingo Vogelsang and Scott Wallsten as well as participants at the 2012 International Industrial Organization Conference and numerous university seminars. We also appreciate the industry and network insights gained from conversations with James Eisner, Donald Johnson and Thomas Spavins of the Federal Communications Commission (FCC) and Robert Roche of the Cellular Telephone and Internet Association (CTIA). Finally, we express our gratitude to Stephen Blumberg and Robert Krasowski at the Centers for Disease Control (CDC), who were instrumental in our efforts to assemble a large and complex database. We alone remain responsible for any and all errors.

# 1 Introduction

The emergence and rapid proliferation of wireless telephony and broadband service have introduced the most dramatic transformations in the telecommunication industry since the invention of the telephone in 1876. When Ameritech first introduced cellular service in the United States in 1983, however, few would have imagined its explosive growth potential. After all, the first wireless phones were large, weighing over two pounds each, and airtime prices were nearly $1 per minute.[1] Yet by 2012, the technology had improved significantly and the prices of wireless handsets and subscription services had fallen dramatically. The result: over 300 million wireless subscribers in the U.S. alone and roughly 6 billion wireless subscribers worldwide.[2] Over 30 percent of all U.S. households today are wireless-only.[3]

The rapid pace of consumer demand, technology and public policy changes in this industry has raised a number of important questions that economists have only recently begun to address. Prominent among these questions is how the presence of wireless telephony affects households' choices as they seek to have their communications needs met. Insights into this question promise, in turn, to shed light on a number of current economic policy questions, including whether wireline and wireless services are better described as complements or substitutes, whether traditional public policy efforts to promote wireline subscription to the public switched network are necessary in light of the rapid wireless services adoption, and whether competition between wireline and wireless platforms is sufficient to warrant a "light-handed" approach to industry regulation. Additionally, the emergence of wireless technologies also raises broader questions regarding the potential for improved efficiencies in specific industries, such as health care, education, insurance, agriculture and fishing, as well as to the broader economy.[4]

Two threads of economic research have emerged which provide some assistance in addressing the issue of household telephony choices in an environment that includes wireline and wireless options. The first is a rich literature on the demand for wireline telecommunications.[5] The second is a more recent literature on the diffusion of wireless telephony.[6] While both research threads are informative, neither captures the rich evolution of consumers' decisions regarding their telecommunications portfolios over the past decade. In particular, given the dramatic evolution of wireline and wireless services, natural questions arise regarding the economic motivations driving adoption when consumers now have multiple options to satisfy their communications needs, including wireline service only, wireless service only, both wireline and wireless services, and neither wireline nor wireless service.

[1] Mayo and Woroch (2010).

[2] International Telecommunication Union (2012).

[3] See Blumberg and Luke (2011). Following their terminology, we refer to "wireless" as what alternatively is termed "mobile", "cell", or "cellular" service.

[4] For industry-based studies of the impact of advanced telecommunications, see, e.g., Brown and Goolsbee (2002), Jensen (2007) and Aker (2010). See Röller and Waverman (2001) for a study of the macroeconomic consequences of the deployment of advanced telecommunications.

[5] For a detailed review, see Taylor (2002).

[6] Vogelsang (2010) provides a thorough review of the diffusion of wireless telephony, including studies using microdata from the early 2000s that seek to estimate evidence of consumer substitution across fixed (wired) and mobile (wireless) services. See, e.g., Rodini, Ward and Woroch (2003) and Ward and Woroch (2010). For a literature survey of economic issues related to the wireless telephone industry, see Gans, King and Wright (2005).

In this paper, we take a step toward understanding the evolution of telecommunications demand in the context of an environment in which consumers face a portfolio-choice. We do so by first developing a simple model of household choice for alternative platforms that satisfy their communications needs. One alternative is a high quality wireline platform that provides telecommunications services between wired nodes, but is incapable of providing communications for consumers who are not physically located at such nodes. Another choice is (initially) a lower quality wireless platform, but offers consumers the ability to communicate while away from the wired nodes. Other household choices include the selection of both platforms or neither platform. Our model provides insights into the household and network characteristics that are likely to arise as key determinants of the choices that households make regarding how to satisfy their communications needs. We also explore conceptually the implications and interpretations of consumer patterns of substitution across platforms in the face of alternative prices. This approach allows us to frame an empirical analysis that explores both non-price and price determinants of demand, including the substitutability or complementarity of wireline and wireless services.

Given this model, we then draw upon a large and unique survey of household-level communications platform choices over 2003-2010 to empirically model households' decisions to adopt wireline services, wireless services, both services, or neither service. The estimations provide consistent support for the conceptual framework. In particular, households whose characteristics indicate spatial mobility of household members are significantly more likely to gravitate toward portfolio choices that include wireless telephone service. And conversely, households whose characteristics signify greater attached to their homes are more attracted to wireline telephone service. Our empirical analysis also provides strong evidence that wireless telephony has become a close substitute for wireline telephony over the 2003-2010 period.

# 2 A Model of Consumer Choice in a Wired and Wireless Environment

## 2.1 Substitution Patterns: Nonprice Considerations

Consumers' demand for telecommunications services is a consequence of the desire both to be able to transfer information (i.e., voice, data or video) to others and to be able to receive information from others when sufficiently spatially separated to make direct communications difficult. Historically, telecommunications has been available only at fixed (wireline) nodes, so telephone calls from one consumer to another were characterized by exact physical locations. Within this context, models of telephony demand emerged in the 1970s. Over time these models have sought, for example, to capture the essence of network externalities [e.g., Rohlfs (1974)], to model consumer demand in the presence of multiple nonlinear pricing options [e.g., Train, McFadden and Ben-Akiva (1987)], and to model the role that local and long-distance service boundaries and pricing play on telecommunications demand [e.g., Martins-Filho and Mayo (1993)].

While advancing understanding of the demand for traditional telephone services, these models have not typically allowed for consumer preferences to reflect a desire (or an ability) to communicate away from fixed nodes. That is, communications demand was driven by the utility of a consumer $i$, located at node $N_i$, to communicate with another consumer $j$, $j = 1 \ldots m$, located at $N_j$, by either making or receiving telephone calls between $i$ and $j$.[7] The emergence of wireless telephony, however, provides the opportunity for a broader description of consumer demand. In particular, while consumers may retain the demand for $N_i$ to $N_j$ communications, they may also gain utility from being able to reach other consumers who are not at a wireline node. Similarly, a consumer $i$ may also gain utility from the ability of another consumer $j$ to reach her while she is away from her node.[8]

Thus, if we let $N_iN_j$ represent calls (or the prospect of calls) between consumers $i$ and $j$ that originate at $N_i$, the utility of $i$ in a wireline-only world can be fully characterized by:

$$u_i = \sum_{j=1}^{m} u(N_iN_j) + \sum_{j=1}^{m} u(N_jN_i). \tag{1}$$

Allowing for the possibility of wireless communications, we can now represent a consumer $i$'s utility from telecommunications services more fully by:

$$u_i = \sum_{j=1}^{m} u(N_iN_j) + \sum_{j=1}^{m} u(N_jN_i) + \sum_{j=1}^{m} u(N_iW_j) + \sum_{j=1}^{m} u(W_iN_j) + \sum_{j=1}^{m} u(W_iW_j)$$

$$+ \sum_{j=1}^{m} u(N_jW_i) + \sum_{j=1}^{m} u(W_jN_i) + \sum_{j=1}^{m} u(W_jW_i)^{9} \tag{2}$$

where the $W$s represent communication using wireless technologies.

Two features of wireless services point toward a more nuanced specification of eq. (2). First, while in theory wireless telephony may provide ubiquitous calling, in practice wireless networks may not be sufficiently developed to provide communications services throughout a consumer's relevant region.[10] Thus, if we let $\lambda$, $0 \leq \lambda \leq 1$, represent the proportion of a region served by wireless providers, we can more accurately represent eq. (2) by discounting the utility afforded from wireless calling to and from areas in which wireless coverage does not exist. Second, provided that coverage does exist, the wireless transmission quality may be lower than that of wireline telephony. This lower quality may be due to either inadequate infrastructure development in a nascent (or even mature) wireless network or physical challenges caused by manmade or natural topography. Such reduced transmission quality may

[7] Of course, households also may place value on the option to make or receive calls between nodes.

[8] It is also possible that wireless service may not only afford mobility, but also enhance communications services breadth. This would happen, for instance, if wireline broadband service was unavailable while broadband service was available via wireless technologies.

[9] We follow the convention first established by Rohlfs (1974, p. 20) in assuming that interrelationships between the demand for telecommunications services and other non-communications services purchased by consumers can be ignored. Similarly, we eschew (for the moment) a discussion of the effects of pricing on consumption patterns. We return to this below, however, in Section 2.2.

[10] The size of the relevant region depends on the geographic scope of a consumer's calling patterns. In some cases, virtually all of a consumer's desired calling is within a small geographic area. In other cases, however, it may be quite large. The potential lack of ubiquity regarding wireless networks holds regardless.

be in the form of increased dropped calls, slower data transmission, or the like. Thus, letting $\delta$, $0 \leq \delta \leq 1$, be the quality discount of wireless service relative to wireline service, we then specify:

$$W_i^* = (1 - \lambda)(1 - \delta)W_i \text{ and}$$

$$W_j^* = (1 - \lambda)(1 - \delta)W_j \tag{3}$$

where $W_i^*$ and $W_j^*$ represent the ubiquity- and quality-adjusted level of wireless services available to consumers $i$ and $j$, respectively. Substituting eq.(3) into eq. (2) gives:

$$u_i = \sum_{j=1}^{m} u(N_iN_j) + \sum_{j=1}^{m} u(N_jN_i) + \sum_{j=1}^{m} u(N_iW_j^*) + \sum_{j=1}^{m} u(W_i^*N_j) + \sum_{j=1}^{m} u(W_i^*W_j^*)$$

$$+ \sum_{j=1}^{m} u(N_jW_i^*) + \sum_{j=1}^{m} u(W_j^*N_i) + \sum_{j=1}^{m} u(W_j^*W_i^*) \tag{4}$$

For consumer $i$, the incremental utility associated with subscribing to wireless service depends on: (a) whether consumer $i$ has a demand to communicate with other consumers ($j = 1 \ldots m$) while $i$ is away from his node; (b) the probability of consumer $i$ being at his node at the time that $i$ to $j$ communications is desired;[11] (c) the ubiquity of wireless coverage; (d) the quality of wireless service relative to wireline service; and (e) the utility to consumer $i$ of being reachable by the other consumers $j$ when $i$ is away from his node.

## 2.2 Substitution Patterns: Price Considerations

Turning to the effects of pricing on consumer substitution, our goal is to determine the economic relationship between wireline services and wireless services. In particular, we seek to determine whether access to wireless service serves as a complement to, or substitute for, access to wireline service. As such, the central questions are ones of consumers' responsiveness to pricing changes in nodal wireline services ($N$) and wireless services ($W$). Wireline telephone service is typically priced as a lump-sum monthly payment with a zero marginal price per minute of use.[12] Similarly, wireless telephone service pricing plans most typically

[11] We abstract away from the potential for households to gain utility from asynchronous communications such as voicemail, email, video and file transmissions that are not received simultaneously. We also implicitly assume that the wireless device is "turned on" while individuals are away from their nodes rather than receiving a message and subsequently returning the call at a later time. Incorporating these considerations would involve discounting the utility from fully contemporaneous communications without any harm to the basic approach we adopt here. We also abstract away from the distinction between the called party being at her node from the called party being at any wired node. In our empirical analysis, however, we account separately for these possibilities.

[12] We set aside here the rather *de minimis* portion of consumers who subscribe to local wireline telephone service on a usage basis.

incorporate allowances for a number of minutes that have a zero marginal price as long as the consumer's usage does not exceed the allowance. In these circumstance, the consumer's subscription will depend on a comparison of the monthly subscription fees of wireline and wireless services to the amount of consumer surplus enjoyed from wireline and wireless usage, after consumers have paid their respective monthly fixed charges.[13]

Across the various options for consumers to satisfy their telecommunications needs, let $P_{i,\Psi_k}$ represent the monthly access price paid by consumer $i$ for consumption bundle $\Psi_k$, $k = 0 \ldots 3$. With the introduction of a wireless service option, consumers face a portfolio choice:

(1) The household chooses to not subscribe to either wireline or wireless service - $\Psi_0$;

(2) The household chooses to subscribe to only wireline service - $\Psi_1$;

(3) The household chooses to subscribe to both wireline and wireless service - $\Psi_2$; or

(4) The household chooses to subscribe to only wireless service - $\Psi_3$.

Consumer decisions among these choices will be driven by a consideration of the utility associated with these four mutually exclusive options and the relative prices imposed by each. If we let $M_i$ represent household income, individual consumers can be seen to choose $\Psi_k$ over alternatives $\Psi_z$ ($\Psi_z \neq \Psi_k$) whenever:

$$u_i(\Psi_k; M - P_{i,\Psi_k}) > u_i(\Psi_z; M - P_{i,\Psi_z}), \text{for all } z. \tag{5}$$

Normalizing consumers' utility by the "outside good" ("off-the grid") option, and letting utility depend both on a deterministic component $\mu$ and unobservable variations in utilities $\nu_N$ and $\nu_W$ that vary across decision-making units, we can specify:

$$\begin{aligned}
&u_0 = 0, \text{the utility derived when the household chooses to remain "off the grid"};\\
&u_N = \mu_N + \nu_N = X_N\beta_N - \alpha P_N + \nu_N, \text{the utility from wireline-only subscription};\\
&u_W = \mu_W + \nu_W = X_W\beta_W - \alpha P_W + \nu_W, \text{the utility from wireless-only subscription};\\
&u_{NW} = u_N + u_W + \Gamma = \mu_N + \mu_W + \nu_N + \nu_W + \Gamma, \text{the utility from wireline and}\\
&\text{and wireless subscription};
\end{aligned} \tag{6}$$

where $X$ is a standard set of explanatory variables, $\alpha$ and $\beta$ are vectors of parameters to be estimated and $\Gamma$ is the incremental utility from consuming both services rather than either one separately. Following Gentzkow (2007), we specify:

$$\Gamma = (u_{NW} - u_W) - (u_N - u_0) \tag{7}$$

which measures the extent to which the consumer enjoys added utility of nodal wireline service if wireless service is also consumed. In this model, the utility associated with subscribing to both services is therefore not the simple sum of utility for each one. When $\Gamma > 0$, there is a "bonus" utility from subscribing to both services, and so indicates a complementarity from

[13] See Taylor (2002).

joint consumption. When $\Gamma < 0$, some utility is lost relative to the simple sum. Provided there is still a net gain from adding the second service, it is consistent with substitutability of the services. For these reasons, we follow Gentzkow (2007) and state that wireline service is a *substitute* for mobile service if and only if $\Gamma < 0$. Similarly, wireline service is a *complement* to wireless service if and only if $\Gamma > 0$. If $\Gamma = 0$, the services are independent.[14]

For any given decision-making unit, let $\pi_j$, $j = N, W$ represent the probability of choosing either nodal wireline service $N$ but not wireless service or choosing wireless service $W$ but not nodal wireline service, and let $\pi_{NW}$ be the probability of choosing both wireline and wireless service. The probability of choosing no service $\pi_0$ is linearly dependent and can be determined by examination of the other probabilities. Assuming that consumers maximize utility, the probability that a consumer will choose one of the four options is:

$$\pi_j = \int_{\vec{\nu}} \mathbf{I}\{u_j > u_0, u_j > u_k, u_j > u_{NW}\} dF(\vec{\nu}) - \text{the probability of the } j^{th} \text{ service alone}$$

$$\text{where} j \neq k,$$

$$\pi_{NW} = \int_{\vec{\nu}} \mathbf{I}\{u_{NW} > u_0, u_{NW} > u_N, u_{NW} > u_W\} dF(\vec{\nu}) - \text{the probability of both services,}$$

$$\pi_0 = \int_{\vec{\nu}} \mathbf{I}\{u_0 > u_N, u_0 > u_W, u_0 > u_{NW}\} dF(\vec{\nu}) - \text{the probability of neither service.} \quad (8)$$

To generate insights into the degree of substitutability or complementarity of consumers' demand for wireline and wireless services we explore how the probabilities in equation (8) are affected by variation in the prices of wireline and wireless services. In this regard, we focus on the (subscription-based) quantities of wireline services ($Q_N = \pi_N + \pi_{NW}$) and wireless services ($Q_W = \pi_W + \pi_{NW}$). We can then define the economic relationship between nodal wireline and wireless services as:

$$\frac{\partial Q_W}{\partial P_N} = 0 - \text{Wireline and wireless services are independent,}$$

$$\frac{\partial Q_W}{\partial P_N} > 0 - \text{Wireline and wireless services are substitutes,}$$

$$\frac{\partial Q_W}{\partial P_N} < 0 - \text{Wireline and wireless services are complements.} \quad (9)$$

Figure 1 shows this relationship visually and demonstrates the critical role played by $\Gamma$. This figure depicts the demands for wireline and wireless services in utility space.[15] As driven by the utilities depicted in eq. (6), consumers choose among the four depicted portfolio choices. Consider panel (a), which depicts the situation in which wireline and wireless services are independent. In this case, an increase in wireline service price will cause a marginal consumer (shown as $j$) to switch from purchasing the $NW$ bundle to purchase

[14]For a formal proof, see Gentzkow (2007).

[15]Figure 1 is an adaptation of Gentzkow (2007) to the case of nodal wireline and wireless services.

$W$only.[16] It also results in some marginal consumers (shown as $k$) to switch from $N$ only to the outside option of no telephone service. Notice, however, that the change in the price of $N$ has no effect on the demand for (i.e., subscription to) $W$, hence the independence of the services.

Next consider panel (b), which depicts the situation in which wireline and wireless services are complements ($\Gamma > 0$). Given equation (6), the boundaries between consumers' portfolio choices are shown as heavier-shaded lines. Given a price increase in $N$, marginal customers designated by $j$ and $k$ react as described previously. But there are now other marginal consumers designated as $o$ for whom an increase in the price of $N$ is met with a switch from consuming both services to consuming neither service. In this case, the decrease in $\pi_{NW}$ exceeds the gain in $\pi_W$. Thus, $\frac{\partial Q_W}{\partial P_N} < 0$ and $\Gamma > 0$ keynotes complementarity between $N$ and $W$.

Finally, consider panel (c), which depicts the situation in which wireline and wireless services are substitutes ($\Gamma < 0$). In this case, a price increase in $N$ leads to three sorts of switching. Some consumers of $N$, such as $k$, shift to consume neither $N$ or $W$. Other consumers of $N$, such as $j$, who previously consumed both services now consume $W$ only. Still other consumers of $N$, such as $o$, who previously consumed only $N$ switch to $W$ only. In this case, the decrease in $\pi_{NW}$ will be smaller than the increase in $\pi_W$, so $\frac{\partial Q_W}{\partial P_N} > 0$ and the services are considered substitutes.

# 3 Empirical Setting and Data

To estimate consumer decisions regarding their portfolio of telecommunications choices, we begin with a unique micro-level database assembled by the National Center for Health Statistics (NCHS), which operates as part of the Centers for Disease Control (CDC). NCHS administers the National Health Interview Survey (NHIS) annually as the principal source of information on the health of the U.S. civilian non-institutionalized population. Interviewers visit 35,000-40,000 households and collect data on roughly 75,000-100,000 individuals annually.[17] Our data are over the 2003-2010 period, with nearly 25,000 households surveyed each year. As shown in Appendix A, NHIS-surveyed households generally track U.S. population demographic characteristics closely.[18] Households are queried in this survey regarding their subscription to wireline and wireless telephone services. Of particular interest are questions about whether the household has no telephone, a wireline telephone only, a wireless telephone only, or a wireline telephone and (one or more) wireless telephones.

While the public use portion of the data are helpful, the specific locations of surveyed households remain confidential. By application to and approval from the NCHS, we gained access to the confidential household data maintained at a secure facility in Hyattsville, Maryland. Using household-level geocodes, we are able to link the NHIS survey data to

[16] We consider here the case of a price change for wireline service. A similar construction for wireless price changes is straightforward and, therefore, omitted.

[17] For a detailed overview, see *http://www.cdc.gov/nchs/nhis/about_nhis.htm*.

[18] To provide additional assurance that our empirical analysis is not unduly affected by the sampling methods of the NCHS, we employ the sampling weights established by CDC as a robustness check to the estimations we report in Section 4. The results we report are substantively unchanged by the application of the sample weights.

location-specific data from several public data sources, including the Federal Communications Commission, the United States Census Bureau, the United States Bureau of Labor Statistics and the United States Department of Agriculture. We describe these other data sources below.

## 3.1 Data Overview and Summary Statistics

The combined dataset for empirical analysis includes 189,616 observations over the 2003-2010 period. Table 1 provides summary statistics on households' subscription to wireline and wireless services, while Figure 2 shows the evolution of households' portfolio choices over time.[19] Several characteristics of households' portfolio choices are noteworthy. First, the proportion of households not subscribed to any telephony service is small (about one percent) and remains so throughout the sample period. Second, the proportion of households subscribed exclusively to wireline service decreased dramatically from roughly 49 percent in 2003 to just over 12 percent in 2010. Third, the corresponding share of households subscribing exclusively to wireless telephony grew over the sample period from roughly four percent in 2003 to approximately 31 percent in 2010. Finally, households subscribing to both services grew at the beginning of the sample period from 46 percent to a peak of 61 percent in 2007 and has subsequently declined to 55 percent in 2010.

The data also reveal important subscription pattern differences by household income. Figure 3 shows the evolution of telephone portfolio choices for households that are below the poverty thresholds in each year. By 2010, the share of poor households subscribing to wireless services only (around 44 percent) was significantly higher than the share of all households subscribing to wireless services only (around 31 percent). Similarly, by 2010 poor households subscribed in larger proportions to wireline service only (roughly 20 percent) in comparison to all households (roughly 12 percent).

Finally, the data point to important changes in telephone portfolio choices by household age. Figure 4 shows that the movement to wireless-only consumption has been particularly dramatic for young households (household members less than 31 years old) over the 2003-2010 period. In 2003, nearly 13 percent of young households subscribed exclusively to wireless services and over 85 percent subscribed to either wireline service only or both wireline and wireless services. But by 2010, over 70 percent of young households subscribed only to wireless service, while the share subscribing to wireline only had fallen to under four percent and the share subscribing to both services had fallen to roughly 23 percent.

## 3.2 Variables

Our effort to capture variations in observed household telephone portfolio choices focuses on four categories of variables. First, based on the Section 2.1 discussion, we include variables that are designed to capture the degree to which household members are affiliated more closely with their domicile (node), or alternatively are considered more mobile. Second, we incorporate measures of the respective prices of wireline and wireless telephone service, along with measures of household income. Third, we include measures that seek to capture

[19]The data shown in Figure 2 are unweighted. Weighted observations yield essential the same pattern as what is reported here.

the wireless telecommunications quality relative to the wireline network. Finally, we include measures to account for demographic characteristics of households. We provide a general overview of these variables below, but a more detailed set of variable definitions and sources is provided in Appendix B.

**Nodal Variables** Several variables are included to capture the degree to which household members are more (less) closely affiliated with their nodal domicile. Because older households typically spend a greater proportion of their time at home,[20] we include several age-related variables. We first account for whether the household includes a retired individual (*Retired Household*).[21] We next account for whether the household consists solely of individuals under age 31 (*Young Household*), between ages 31 and 45 (*Young-Middle Household*), between ages 45 and 64 (*Older-Middle Household*), or over age 64 (*Older Household*). We expect that older or retired households will be more closely affiliated with their node and will therefore be more prone to subscribe to wireline service than wireless service. Conversely, we expect that younger households will be attracted in greater proportions to wireless service, as it enhances their abilities to communicate while being "on the go". While more mobile lifestyles among younger households may be thought to create greater attraction to wireless telephony than older households, it is also possible that older consumers are leary of "new" technologies, and will remain loyal to wireline telephony longer than younger households. To account for this potential, we also account for whether an older household is also wealthy (*Wealthy Retired Household*). We expect that wealthier elderly households will be more mobile and less intimidated by new technologies, thereby enhancing wireless telephony subscription.

We also account for household nodal demographics by including measures of whether the household has children (*Children*) and whether any children are students (*Student*). Our expectation is that parents place high priority on "anywhere, anytime" communications with children and students, and will accordingly have enhanced demand for wireless services relative to households without children and students. At the same time, children and students create greater attachment to the family domicile, so we also expect that children and students will create a greater propensity for the household to subscribe to wireline service.

A unique feature of our data is that it includes measures of the health of household members. To take advantage of this information, we account for potential health-related impacts on households' telephone portfolio choices. In particular, we account for households that have a health-impaired youth (*Limited Youth*) or health-impaired adult (*Limited Adult*). Our expectation for the former is that such households have a greater demand for "anywhere, anytime" communication and will therefore be more inclined to include wireless telephony in their portfolio, while our expectation for the latter is that such households have a stronger nodal presence and corresponding need for wireline service.

We also account for the working status of the household via several variables. We first account for the ratio of household members employed outside the home (*Ratio Working*). We suggest that work-related matters take household members away from their domicile, making nodal wireline service less attractive and wireless service more attractive. We also

[20]Bureau of Labor Statistics (2011).

[21]We alternatively substituted this variable with one that accounted for whether the surveyed household included a member that draws Social Security benefits. There was virtually no change in the subsequent empirical results.

account for whether any household member is employed part-time *(Part-time Employed)*. Given the mobile nature of such households, we expect that part-time employment will be associated with an enhanced propensity to subscribe to wireless service. But a household member that is only employed part-time signals greater attachment to the domicile, and therefore likely enhances wireline service demand. We also account for whether a member of the household has self-identified as a housewife (*Housewife*) to examine whether this creates a greater nodal presence and, hence, attraction to wireline services.

Given the efficiency gains from the wider reach [c.f., Jensen(2007)] and the security benefits of mobile telephony in rural areas, we include a measure of the degree to which the household is located in more sparsely populated areas. In particular, we include a variable to capture the population density of the county within which the household resides (*Population Density*). We expect that for a given wireless infrastructure quality level, the propensity of rural households to subscribe to wireless telephony will be enhanced.

Finally, we account for domicile ownership using an indicator variable that differentiates between households that own their home versus rent (*Own House*). Our expectation is that ownership signals greater nodal attachment, with a corresponding increase in the propensity toward wireline telephony services.

**Price and Income Variables** Prices are at the heart of demand theory. Accordingly, we include measures of the individual prices of wireline and wireless services. To capture variations in wireline service prices, we begin with 2002 data on the basic flat monthly charges by wire center throughout the U.S.[22] Because the areas served by wire centers are not typically contiguous with county boundaries, we use population weights within individual wire centers to construct a weighted price by county for residential landline service throughout the U.S. To update these data for the larger sample period, we utilize the Federal Communication Commission's (FCC) "Reference Book of Rates, Price Indices, and Household Expenditures for Telephone Service" (Reference Book). In particular, the Reference Book reports the results of an annual survey of local monthly fixed telephone rates for 95 cities located throughout the U.S. The year-to-year values of Pearson correlations for prices in these cities are very high, averaging .96 across for the relevant time period, indicating that the principal source of wireline rate variation is captured by our spatial disaggregation of prices at the sample period beginning. Accordingly, *Wireline Price* is updated by the values of Consumer Price Index (CPI) for local exchange service for the 2003-2010 period.[23]

We also include the price of wireless telephone service subscription. While numerous wireless subscription plans exist, they most generally entail a flat rate charge for a "bucket" of minutes. For consumers whose usage levels remain within the purchased bucket, the price can be taken as the average monthly expenditure for the service. Data on the average monthly

[22]These data were graciously provided to us by Greg Rosston, Scott Savage and Bradley Wimmer. See Rosston, Savage and Wimmer (2008) for a detailed description of these data. While many local telephone companies offer local measured service in which customers pay a smaller monthly subscription charge and (after a call or minute allowance) pay a marginal charge per minute or call, industry sources report that the percentage of customers who avail themselves of this option is *de minimus*. Accordingly, we focus on consumers' choices based on variations in flat monthly rates. For a detailed study of the economics of such optional calling plans, see Miravete (2002).

[23]Robustness checks of our estimations that employed alternative price measures, such as measures of annual telephone CPI variations or CPI ratios for local and wireless telephone service, gave results that are very similar to those reported below.

revenue per user (including roaming charges and long distance toll calling) were provided to us by the Cellular Telephone and Internet Association (CTIA). We rely upon *Wireless Industry Indices*, a semi-annual survey conducted by CTIA of its member companies. In the survey, data were received by companies representing over 95 percent of all U.S. wireless subscribers, and are provided for the 2003-2010 period. While wireless prices are typically geographically invariant, state and local taxes impose spatial variations in the prices paid by consumers in different locales. To capture these variations, we incorporate state and local tax data provided by the Committee on State Taxation (COST). The data are derived from a series of studies conducted by COST, beginning in 1999 and repeated thereafter every three years (i.e., 2001, 2004, 2007 and 2010),[24] which report the prevailing state sales tax rate inclusive of general sales taxes. Local tax rates for each state were taken to be the average between those imposed in the largest city and the capital city. Federal taxes were reported separately. Any flat fees (e.g., 911, Universal Service Fund) were converted to percentages based on average monthly residential bills. In the first two reports, a single tax rate was provided that blended the state and local taxes applied to wireline local and long distance service, and mobile service. In later reports, taxes levied specifically on wireless service were reported separately. After incorporating state and local taxation variations, our measure of *Wireless Price* entails both spatial and inter-temporal dimensions over the relevant period.[25]

As is common in modern demand estimation, we consider the potential endogeneity of prices which in our case may most directly be thought to arise either from omission of relevant exogenous variables (or product characteristics) or from a causal feedback from observed demand on prices. In the case at hand, however, potential endogeneity concerns are tempered somewhat by two considerations. First, while a common source of endogeneity bias arises from the omission of relevant independent variables our model includes a wide-ranging and substantial number of explanatory variables that may reasonably be thought to collectively mitigate this source of endogeneity bias. Second, in our case feedback from observed demand on prices is mitigated by the particular price-setting mechanisms in the telecommunications industry. Specifically, wireline prices are determined by the regulatory process, which in large part is driven by supply-side (cost) considerations. This is most obviously true for traditional rate-base/rate-of-return regulation. It is also true, however, for price cap regulated firms, whose initial prices under price cap regulation were most often set by existing rates that were established under rate-of-return regulation. Subsequent price changes under price cap regulation have most typically been driven by changes in measures of general inflation (e.g., the CPI) and productivity changes, neither of which tends to be driven by market demand. Similarly, geographic variations in the price of wireless telephony are captured by variations in state and local tax differences, which are, again, not driven in any obvious way by market demand and are exogenous to the carriers. While these considerations ameliorate endogeneity concerns, as described below we nonetheless incorporate econometric methods based on Rivers and Vuong (1988) and Petrin and Train (2010) to assure the integrity of the parameter estimates and their corresponding statistics.

Drawing on the NHIS survey data, we also include measures of household income. Household income is categorized relative to an annual poverty threshold using four dichotomous

[24] See COST (2002, 2005) and Mackey (2008, 2011).

[25] We examined alternative constructions of the wireless price variable in the estimations reported below with essentially no substantive differences from those reported here.

variables. Household income below the poverty threshold (*Income1*), between one and two times the poverty threshold (*Income2*), between two and four times the poverty threshold (*Income3*), and more than four times the poverty threshold (*Income4*) are relevant categories.

**Quality Variables** Consistent with Section 2, we seek to capture both intertemporal and geographic variations in the relative quality of wireline and wireless services. Given that wireline service has been engineered to very high levels with *de minimis* blocking rates over our sample timeframe, we principally focus our efforts on quality variations in wireless services. Wireless service quality is affected by both topographical characteristics of the local calling area and the extent of infrastructure build out. We accordingly gathered data from the United States Geological Survey (USGS) on the extent to which the hilliness or mountainous nature of the local terrain may impair wireless communications quality. *Mountainous* is coded on a 21 point scale ranging from flat plains (1), to open low hills (13), and to high mountains (21). We also account for the provisional challenges of high quality wireless service poised by large bodies of water, and accordingly gathered data from the United States Department of Agriculture (USDA) to account for the percentage of the household's county that is water (*Water*).

As noted in Section 2, the quality of wireless services may suffer either from lack of geographic coverage or from insufficient capacity relative to demand (leading to dropped calls). Wireless industry infrastructure grew significantly over the 2003-2010 period, with corresponding increases in the ubiquity of coverage and call quality. To capture this variation, we include a measure of the number of cellsites deployed over time (*Cellsites*).[26]

Finally technological changes over the past decade have brought notable changes to the versatility (quality) of wireline telephony. Specifically, during the first decade of the 2000s, wireline broadband was increasingly deployed across the United States. Concurrent with the deployment of wireline broadband, providers of both telephone service and cable television began to introduce bundled offerings of these services with high-speed internet access.[27] To account for the potential demand effects of this increased versatility of the wired connections into households, we introduce *Wireline Broadband* which measures the proportion of households within a state over time that subscribe to wireline broadband services.[28]

[26] In the initial years of cellular telephony, cell sites were typically large stand-alone towers. Over time, providers have deployed quality and capacity enhancing antennae on large buildings, utility poles, water towers, etc., so that "towers" are no longer the most accurate measure of wireless capacity. We therefore draw upon a broader measure of cell sites made available by CTIA, which includes repeaters and other cell-extending devices but excludes microwave hops. Because the specific cell site locations are proprietary, we are unable to account for their geographic distribution. More recent deployments of wireless repeaters and antennae have greater coverage and capacity-enhancing characteristics than earlier vintage deployments. Also, wireless network capacity depends upon the "back-haul" capacity of cell sites which carry wireless traffic to the landline network. Increasingly, such "back-haul" is provided by high-capacity fiber which dramatically increases the ability of specific cell sites to handle larger volumes of voice, data and video traffic. Accordingly, our count of cell sites may underestimates the actual wireless capacity and quality increases over time.

[27] See Prince and Greenstein(2011)

[28] As a robustness check, we also drew directly on state-level data collected by the FCC over the 2008-2010 period on households that explicitly subscribed to wireline telephony as part of a bundled offering. The results of this alternative estimation are substantively invariant to those reported in Section 4 below, but involve sacrificing approximately 100,000 observations over the 2003-2007 period. Acordingly, we report our the estimations using *Wireline Broadband* in Section 4 below. In addition to our measure of wireline broad-

**Demographic Variables** Finally, the existing literature has identified a number of demographic characteristics that affect the likelihood that households subscribe to the "telephone" network. Riordan (2002) surveys this literature, and also independently verifies several demographic factors as contributing to households' propensities to subscribe to wireline service. We accordingly account for households' racial composition (*White, Black, Hispanic, Asian, Indian,* and *Chinese*), gender composition (*Female Household* and *Male Household*), and marital status (*Divorced*) as controls.

# 4 Estimation and Results

To provide a better understanding of consumer selection of a portfolio of available telecommunications services, we first report correlations between household's subscription to wireline and wireless telephone services. The second column of Table 2 reports tetrachoric correlations for households' decisions to adopt wireless and wireline services, respectively.[29] These estimates represent simple correlations between households' decisions to adopt wireline services with their decisions to adopt wireless services (1 if "yes", 0 if "no"). The pattern of correlations is consistently negative: households that adopt wireless telephony are less likely to adopt wireline telephony ($\rho = -.53$). The observed correlation is statistically significantly different from zero at the .01 level. As seen in Table 2, moreover, this pattern of negative correlations holds not only for the entire sample of surveyed households but also within each sample year and across all income levels, with the largest negative correlations occurring in the lowest income households. These negative correlations point toward the substitutability of wireline and wireless services.

We also report the partial correlation coefficients between wireline and wireless consumption, after controlling for a number of variables, including price, income, demographic variables (*Female/Male Household, Black, Divorced*), nodal variables (*Young Household, Young-Middle Household, Older-Middle Household, Children, Student, Own House, Ratio Working, Part-Time Employed, Retired Household, Wealthy Retired Household, Housewife, Limited Youth, Limited Adult, Unrelated Adults, Population Density)*, and wireless telephony quality variables (*Cellsites, Water, Mountainous, Wireline Broadband*). As seen in Column 3 of Table 2, the relationship between wireline and wireless consumption remains negative ($\rho = -.37$) and is highly statistically significant (even after controlling for several other correlates). The negative correlations again hold not only for the entire sample, but also for each year (with the exception of 2003) and income level. Again, the highest (negative) correlations observed are at the lowest income levels.

To parametrically investigate the empirical relationship between wireline and wireless subscriptions, we employ several discrete choice models. In any discrete choice analysis, the first step is to identify the available choice set. For our purposes, we assume that both wireline and wireless services are in the choice set, as is the option to not subscribe to any telephone service. As described in Section 2, we seek to understand the decisions of

band, we also sought to incorporate the potential demand effects of the emergence of wireless broadband. Unfortunately both the novelty of this phenomenon and inconsistent data collection methodologies by the FCC prohibited our use of such a measure in the estimations.

[29]Tetrachoric correlations are developed for two normally distributed variables that are both expressed as dichotomous. See Greene (2012), p. 741.

households to adopt (or not) either wireline or wireless service.

## 4.1 Bivariate Probit Model

We begin with a simple specification of household decisions to adopt (or not) wireline service and, potentially independently, adopt (or not) wireless service. The results of two probit regressions are reported in Model (a) of Table 3. The first regression estimates households' decisions to adopt wireline service, and the second regression estimates households' decisions to adopt wireless service. The key assumption underlying these probit estimations is that the decisions to adopt wireline service and wireless service are unrelated. To test this proposition, we allow for the possibility that the error structures across these equations are related.[30] We subsequently estimate a bivariate probit model which yokes the decision to adopt (or not) wireline and wireless, respectively, by accounting for common correlation ($\rho$) between the error structure in the two equations.[31] The estimation results are shown in Model (b) of Table 3, and reveal a strong negative correlation ($\rho = -.52$) in the error structure from the two equations that is significantly different from zero ($p = .01$). The hypothesis of independence of these decisions is therefore strongly rejected. The negative and statistically significant correlation indicates that positive random errors to the wireless subscription equation are associated with negative random errors to the wireline subscription equation. Because this association is, by construction, through the error structure no causality can be inferred. The results nevertheless strongly reject the hypothesis that these decisions are made independently by households and are suggestive of the wireline and wireless service substitutability.

To address the endogeneity issues mentioned above we implement Rivers and Vuong's (1988) two-stage conditional maximum likelihood (2SCML) estimation of the probit and bivariate probit models. In our case, the models are estimated using the following system of equations:

$$y_{it} = \sum_{j=N,W} \beta_j Price_{ijt} + \gamma_k X_{it} + \gamma_m Z_{ijt} + \epsilon_{it}, \tag{10}$$

$$\tilde{y}_{it} = \sum_{j=N,W} \kappa_j Price_{ijt} + \xi_k X_{it} + \xi_m Z_{ijt} + \tilde{\epsilon}_{it}, \tag{11}$$

where $y_{it}$ and $\tilde{y}_{it}$ are dummy variables which equal to 1 if a household is subscribed to wireline (respectively, wireless) service at time $t$. $Price_{ijt}$ is the price faced by household $i$ for service $j$ at time $t$, $X_{it}$ is an $k \times 1$ vector of demographic and nodal characteristics of household $i$ in year $t$; $Z_{ijt}$ is an $m \times 1$ vector of quality variables for household $i$ for telephone option $j$ ($j = N, W$) in year $t$ and $\epsilon_{it}$ and $\tilde{\epsilon}_{it}$ are error terms.

Allowing for the potential endogeneity of $Price_{ijt}$, we first estimate

[30] See Greene (2012), p. 738.

[31] For an earlier application of the bivariate approach, see Augereau, Greenstein, Rysman (2006) who model Internet Service Providers' propensities to offer 56K service by utilizing an "X2" modem, a Flex modem, both or neither.

$$Price_{ijt} = \tau_k X_{it} + \tau_m Z'_{ijt} + v_{ijt}, \tag{12}$$

and recover the estimated residuals $\hat{v}_{ijt}$ from equation (12). This in turn allows us to estimate

$$y^{\star}_{it} = \sum_{j=N,W} \beta_j Price_{ijt} + \gamma_k X_{it} + \gamma_m Z_{ijt} + \sum_{j=N,W} \omega_j \hat{v}_{ijt} + \epsilon'_{it}, \tag{13}$$

$$\tilde{y}^{\star}_{it} = \sum_{j=N,W} \kappa_j Price_{ijt} + \xi_k X_{it} + \xi_m Z_{ijt} + \sum_{j=N,W} \theta_j \hat{v}_{ijt} + \tilde{\epsilon}'_{it}, \tag{14}$$

where $Z'_{ijt}$ is an $(m+2) \times 1$ matrix which includes $Z_{ijt}$ and two exclusion restrictions (*Telecommunications Wages, Mobile Penetration*).[32] Here $\beta_j, \omega_j, \kappa_j, \theta_j$, $j = N, W$ are parameters to be estimated, and $\tau_k$, $\tau_m$, $\gamma_k$, $\gamma_m$, $\xi_k$ and $\xi_m$ are vectors of parameters to be estimated. We assume that both ($X_{it}$, $Z'_{ijt}$, $\epsilon'_{it}$, $v_{ijt}$) and ($X_{it}$, $Z'_{ijt}$, $\tilde{\epsilon}'_{it}$, $v_{ijt}$) are i.i.d; ($v_{ijt}$, $\epsilon'_{it}$) and ($v_{ijt}$, $\tilde{\epsilon}'_{it}$) conditional on $X_{it}$ and $Z'_{ijt}$ have joint normal distributions with mean zero and finite positive definite covariance matrices.

In this case

$$y_{it} = \begin{cases} 1, & \text{if } y^{\star}_{it} > c, \\ 0, & \text{otherwise,} \end{cases} \tag{15}$$

and

$$\tilde{y}_{it} = \begin{cases} 1, & \text{if } \tilde{y_{it}}^{\star} > \tilde{c}, \\ 0, & \text{otherwise,} \end{cases} \tag{16}$$

where $c$ and $\tilde{c}$ represent critical cutoff values that trigger household decisions to subscribe to wireline or wireless service, respectively.

For the bivariate probit model we allow correlation between $\epsilon'_{it}$ and $\tilde{\epsilon}'_{it}$ in the second step. That is,

$$\begin{pmatrix} \epsilon'_{it} \\ \tilde{\epsilon}'_{it} \end{pmatrix} |Price_{ijt}, X_{it}, Z'_{ijt} \Bigg) \sim N \left[ \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 & \rho \\ \rho & 1 \end{pmatrix} \right], \tag{17}$$

[32] Our exclusion restrictions seek to capture observable variables that may drive prices but which are not drawn from the demand side. Accordingly, we draw upon measures designed to capture cost variations (and hence indirectly prices) including a measure of telecommunications wages that varies by state and year and a measure of the density of mobile penetration by Economic Area which also varies by year.

where $\rho$ captures the correlation in the errors across equations (13) and (14). The resulting estimates are consistent and asymptotically normally distributed. Our asymptotic covariance matrix of the 2SCML estimator is based on Rivers and Vuong (1988).[33]

After incorporating the interdependence of the wireline and wireless service subscription choice and accounting for endogeneity, the bivariate probit model provides considerable confidence regarding the overall model shown in Table 3, Model (b). A comparison of the portfolio choices predicted by the model and those actually chosen suggests a good fit. The model correctly predicts 68 and 97 percent of households' portfolio decisions in the wireline and wireless equations, respectively. The specific parameter estimates also provide insight into the determinants of households' portfolio choices for telephony service. The nodal variables provide strong support for the concepts advanced in Section 2 above. In particular, households that are more closely attached to their domicile (node) are more likely to subscribe to wireline service and less likely to subscribe to wireless service. For example, households with a retired household member are significantly more likely to subscribe to wireline service and significantly less likely to subscribe to a wireless service. Other age-related variables that characterize household members (e.g., *Young Household* and *Young-Middle Household*) similarly reflect the greater propensity of younger and more mobile households to subscribe to wireless service, and the corresponding decrease in the propensity of these households to subscribe to wireline telephone service.

Households with different levels of work-related attachments to their node are found to be attracted differentially to wireline and wireless services. In particular, *Ratio Working* increases the propensity to subscribe to wireless telephony and decreases the propensity to subscribe to wireline telephony. Households in which a member works part-time (*Part-Time Employed*) are more likely to subscribe to both wireline and wireless service, in comparison to other households. Households with a self-reported *Housewife* appear more more likely to subscribe to wireline service and less likely to subscribe to wireless service, though these results are statistically insignificant.

Households with a health-limited youth (*Limited Youth*) are no different than other households in their propensity to subscribe to wireline service, but as anticipated are significantly more likely to subscribe to wireless service than other households. By contrast, households with a health-limited adult *Limited Adult* are more likely to subscribe to wireline services and less likely to subscribe to wireless services than other households. Households with students (*Student*) have significantly higher propensities to subscribe to wireless telephony, while having significantly lower propensities to subscribe to wireline service. The estimations also reveal that, *ceteris paribus*, households in more rural areas have higher demands for wireless services in comparison to households in more urban areas. Finally, the estimations indicate that home ownership (*Own House*) is strongly associated with subscription to both wireline service and wireless service.

The price and income parameters are also revealing. Consistent with standard demand theory, *Wireline Price* and *Wireless Price* negatively [and statistically significantly *($p = .01$)*] impact the demand for wireline and wireless service, respectively. Beyond the own-

[33]See, in particular, Rivers and Vuong (1988) equations 4.7 and 4.11. Matrices incompatibility prohibits computation of the covariance matrix for recursive bivariate probit model, discussed below, which includes an additional explanatory variable. Nevertheless we provided estimation results from the second step and these are largely consistent with those obtained in the other estimations.

price impact, however, the estimations also reveal that the cross-price effects are positive and highly statistically significant. Changes in the price of wireline service positively impact the demand for wireless service, while changes in the price of wireless services positively affect the propensity to subscribe to wireline service. The estimations indicate that consumers view wireline and wireless telephone subscriptions as substitutes. While the nonlinear nature of the estimations prevents simple interpretations of marginal effects (ME), they are estimable.[34] Specifically, recalling that $Q_n = \pi_N + \pi_{NW}$ and $Q_n = \pi_N + \pi_{NW}$, we estimate the marginal price effects $\frac{\partial Q_N}{\partial P_N}$, $\frac{\partial Q_W}{\partial P_W}$, $\frac{\partial Q_N}{\partial P_W}$ and $\frac{\partial Q_W}{\partial P_N}$. The results are presented in Table 4, and indicate that the own-marginal effects are both negative and statistically significant *(p=.01)*, while the cross-partial derivatives are both positive and highly significant *(p=.01)*. From equation (9), this latter result again indicates that wireline and wireless services display substitutable rather than complementary characteristics over the 2003-2010 period.

We also find (See Table 4) that *Income* is an important determinant to wireline and wireless subscription. In each case, income increments for those below the poverty threshold to higher levels increase subscription to both wireline and wireless services. The marginal effect of an income shift from the lowest to the highest category results in about a six percent increase in the likelihood of wireline service subscription *(p=.01)* and about a 26 percent increase in the likelihood of wireless service subscription *(p=.01)*.

The quality and diffusion of wireless service are also found to affect consumers' telephony portfolio decisions. *Cellsites* is positive and highly significant *(p=.01)*, indicating as expected that quality improvements associated with greater coverage increases wireless telephony subscription. Similarly, the diffusion of wireline broadband is seen to have enhanced the propensity to retain wireline telephone service and stem the move to wireless service. Finally, areas with more challenging topographies, such as mountains or large bodies of water, which reduce wireless service quality are found to reduce wireless subscription.

Among the most substantial changes in households' telephony portfolio over the 2003-2010 period, the shift away from "wireline-only" is perhaps the most dramatic. As Figure 2 indicates, approximately 50 percent of all U.S. households subscribed exclusively to wireline telephony in 2003. That percentage had fallen to 12 percent by 2010. To explore this phenomena in more detail, we bifurcate the sample into an early period (2003-2006) and a later period (2007-2010).[35] Specifically, we decompose the aggregate marginal effects: $-\frac{\partial \pi_N}{\partial P_N} = \frac{\partial \pi_W}{\partial P_N} + \frac{\partial \pi_{NW}}{\partial P_N} + \frac{\partial \pi_0}{\partial P_N}$. This decomposition permits us to see how the marginal reaction of consumers to relative prices has evolved over time. Table 5 shows the decomposition results of the total marginal substitution effect associated with a change in the price of wireline service. In the 2003-2006 period, there is relatively moderate substitution directly away from wireline services. During this period, only about one-half of the marginal substitution from wireline-only customers was the result of households becoming wireless-only, with the other half seemingly trying out wireless telephony but not dropping their wireline service. By the 2007-2010 period, however, the marginal impact on wireline only households was largely toward a wireless-only portfolio choice. That is, the dominant marginal effect to any elevation of wireline prices in the most recent period has been for households to "cut the

[34]In nonlinear models with single-index form conditional means, marginal effects are calculated using the formula $ME_j = \frac{\partial \pi_j}{\partial x_j} \times \beta_j$. In our case, marginal effects are calculated at mean values of independent variables. For the bivariate probit model, we calculate marginal effects for the following probabilities: $\pi_N, \pi_W, \pi_{NW}, \pi_0, \pi_{W|N}, \pi_{N|W}, \pi_N + \pi_{NW}, \pi_W + \pi_{NW}$. (Cameron and Trivedi (2010)).

[35]We find similar patterns emerge if alternative years are chosen for this bifurcation.

cord" and go wireless-only.

## 4.2 Robustness: Alternative Model Specifications

**Recursive Bivariate Probit Model.** Given the highly negative correlation across equations in the bivariate probit estimation, a natural extension is to model households' decisions jointly by explicitly conditioning wireline service decisions on wireless service decisions. To do so, we include *Wireless*, a variable indicating that the household has adopted at least one wireless telephone, as an independent variable in the *Wireline* equation. The resulting model is recursive and, thereby, does not suffer from the typical problems associated with incorporating a dependent variable as an explanatory variable in a multi-equation discrete choice model.[36] Model (c) of Table 3 provides the results, which indicate households that have chosen wireless service are significantly less likely ($p = .01$) to adopt wireline service. Moreover, the marginal impact of wireless service on the probability of wireline service subscription is large. In particular, wireless service subscription reduces the probability of wireline service subscription by 13.9 percent.[37] Even after accounting for the direct negative impact of wireless service subscription on the likelihood of wireline subscription, the recursive bivariate probit estimates yield the same substantive implications as those in the bivariate model presented in Model (b) of Table 3.

**Alternative Specific Conditional Logit (ASC Logit) Model.** To this point, we have permitted households' decisions to adopt wireless and wireline telephony to be related, but not part of a single household decision-making process. To allow for this possibility, we estimate an alternative specific conditional logit model.[38] This model is distinguished by two features. First, it envisions households making single decisions across the full portfolio of service alternatives. In particular, households choose simultaneously to have no service, wireline service, wireless service or both services. Second, unlike a simple multinomial logit model with measured variation in the characteristics across the decision-making units (viz., households), the ASC Logit model also incorporates measured variations in alternatives themselves. In our case, the ASC Logit model incorporates variations in household characteristics (e.g., age, income, mobility) as well as variations in specific telephone alternative characteristics from which households may choose (e.g., quality).

This estimation requires construction of a price array that households face as they consider the entire telephony portfolio. The price facing households that choose no telephone is zero, while the price facing households that subscribe to wireline only or to wireless only is the local wireline price and wireless price, respectively. Households considering subscription to both services face a price equal to the sum of the wireline and wireless services prices.[39]

To estimate telecommunications demand when the consumer simultaneously chooses across multiple options and where the endogeneity of prices may create inconsistent parameter estimates, we employ the control function approach devised by Petrin and Train

[36] See Greene (2012), p. 745.

[37] For purposes of this calculation, we evaluate the right-hand side variables at their mean values.

[38] See Cameron and Trivedi (2010).

[39] We cannot account for any discounts afforded through bundling of wireline and wireless prices, as these data are unavailable.

(2010). In particular, we assume that the utility obtained by household $i$ from service $j$ ($j$ = "*No Phone*," "*Wireline Only*," "*Wireless Only*," or "*Both*") is specified by:

$$u_{ijt} = \alpha Price_{ijt} + \psi_k X_{it} + \psi_m Z_{ijt} + \epsilon_{1ijt} + \epsilon_{2ijt}, \tag{18}$$

where all variables have the same notation as described above in the Bivariate Probit Model section, $\alpha$ is a parameter to be estimated, $\psi_k$ is $1 \times k$ vector of parameters to be estimated and $\psi_m$ is $1 \times m$ vector of parameters to be estimated. The terms $\epsilon_{1ijt}$ and $\epsilon_{2ijt}$ represent the decomposition of the traditional error term into a control function ($\epsilon_{1ijt}$) and a component ($\epsilon_{2ijt}$) that is independent of $Price_{ijt}$. As with our bivariate probit estimations, we account for the potential endogeneity problem that arises with correlation between price and $\epsilon_{1ikt}$. We do this in two steps. First, as in Rivers and Vuong (1988), we estimate an equation for the endogenous independent variable using ordinary least squares:

$$Price_{ijt} = \tau_k X_{it} + \tau_m Z^{'}_{ijt} + v_{ijt}. \tag{19}$$

We assume that $v_{ijt}$ and $\epsilon_{1ijt}$ are jointly normal and $\epsilon_{2ijt}$ is i.i.d. extreme value for all $j$. Residuals ($\hat{v}_{ijt}$) from the first stage are the used to estimate the control function in the second stage. Incorporating the control function, the utility function is:

$$u_{ijt} = \alpha Price_{ijt} + \psi_k X_{it} + \psi_m Z_{ijt} + \sum_{j=N,W} \lambda_j \hat{v}_{ijt} + \epsilon_{2ijt}, \tag{20}$$

where the $\lambda_j$ are parameters to be estimated. The probability that household $i$ chooses alternative $j$ at time $t$ is given by:

$$Pr(y_{it} = j) = \int \mathbf{I}(u_{ijt} > u_{ist}, \forall s \neq j) f(\epsilon_{2it}) d\epsilon_{2it}, \tag{21}$$

where $y_{it}$ represents the choice of household $i$, $f(\cdot)$ is the density of $\epsilon_{2it}$ and $\mathbf{I}(\cdot)$ is the indicator function. We estimate this choice model using alternative specific logit estimation.[40]

Table 6 provides the results of the ASC Logit model, which are similar to those provided in the Bivariate Probit estimation of Table 3. The importance of both the household's nodal propensities as well as price and income are confirmed. The price that households face for their respective portfolio choice is negative and highly statistically significant, indicating that consumers are price sensitive across the various options as they consider their portfolio of telephone services. Similarly, the nodal variable parameter estimates from the ASC Logit model are quite similar in nature to those generated in the Bivariate Probit model, providing reassuring robustness.[41]

[40]Because the second stage of this estimation employs estimated residuals, we must account for this extra variation in the development of the asymptotic sampling variance. We do so by implementing the bootstrap, as in Petrin and Train (2010).

[41]Given the reliance of the ASC Logit model on the assumption of the independence from irrelevant alternatives, we also estimated a Multinomial Probit model. Parameters from this estimation failed to reveal any notable differences in the interpretations suggested by our other model estimates.

# 5 Conclusion

The introduction of new products or services with new technologies and characteristics presents a number of challenges to traditional demand analysis. Faced with this situation, consumers may replace or augment their existing consumption portfolios. In particular, the new product or service may serve as either a substitute or complement to the existing product or service. In this regard, the advent and diffusion of wireless telecommunications has radically altered traditional consumption patterns among consumers, creating a natural opportunity to consider telecommunications demand with a portfolio choice lens.

In this paper, we develop an economic framework capable of capturing the pattern and evolution of telecommunications consumers' portfolio consumption choices. In doing so, we provide several contributions that may serve as a platform for subsequent research. First, we formulate a portfolio choice framework for how households satisfy their communications needs. Second, within that portfolio choice model, we develop a theory of why (non-price) characteristics of households, especially related to their "nodal tendencies", affect their subsequent telephony portfolio choices. Third, the portfolio choice framework sheds considerable light on the "substitutes versus complements" issue that underpins competition and regulatory policies toward the telecommunications industry. Fourth, given the window of our data from 2003-2010, we are able to observe empirically how variations in the quality and ubiquity of the "new service" affects consumers' portfolio choices.

The empirical results provide considerable support for the approach that we have adopted. In particular, we find that variations in household's nodal characteristics serve as important drivers of households' portfolio choices of telephone service. Households that are more closely attached to their domiciles are more attracted toward wireline service, while households with more mobile lifestyles are more attracted to wireless telephony. The results also consistently and robustly reveal that wireline and wireless services have become substitutes. Finally, variations in the quality and ubiquity of wireless telephony are found to be important determinants of wireless telephony subscription growth relative to wireline telephony over the 2003-2010 period.

## APPENDIX A

### COMPARISON OF NHIS AND THE US CENSUS BUREAU DEMOGRAPHICS

| | General Demographic Characteristics: July 2006 | NHIS Sample 2006 | General Demographic Characteristics: July 2007 | NHIS Sample 2007 | General Demographic Characteristics: July 2008 | NHIS Sample 2008 | General Demographic Characteristics: July 2009 | NHIS Sample 2009 |
|---|---|---|---|---|---|---|---|---|
| **SEX AND AGE** | | | | | | | | |
| **Male** | **49.27%** | **48.28%** | **49.29%** | **48.35%** | **49.31%** | **48.35%** | **49.33%** | **48.19%** |
| Female | 50.73% | 51.72% | 50.71% | 51.65% | 50.69% | 51.65% | 50.67% | 51.81% |
| Under 5 years | 6.82% | 7.37% | 6.87% | 7.71% | 6.91% | 7.50% | 6.94% | 7.37% |
| 5 to 9 years | 6.58% | 7.79% | 6.58% | 7.79% | 6.60% | 7.70% | 6.71% | 7.90% |
| 10 to 14 years | 6.89% | 7.69% | 6.74% | 7.81% | 6.60% | 7.50% | 6.51% | 7.65% |
| 15 to 19 years | 7.12% | 7.46% | 7.12% | 7.54% | 7.08% | 7.38% | 7.02% | 7.50% |
| 20 to 24 years | 7.05% | 6.63% | 6.97% | 6.49% | 6.93% | 6.50% | 7.02% | 6.19% |
| 25 to 34 years | 13.50% | 13.29% | 13.46% | 13.31% | 13.46% | 13.47% | 13.54% | 13.15% |
| 35 to 44 years | 14.58% | 14.64% | 14.31% | 14.44% | 13.98% | 14.01% | 13.53% | 13.89% |
| 45 to 54 years | 14.46% | 14.06% | 14.55% | 14.14% | 14.59% | 14.22% | 14.52% | 14.28% |
| 55 to 59 years | 6.09% | 5.66% | 6.05% | 5.54% | 6.11% | 5.95% | 6.18% | 5.91% |
| 60 to 64 years | 4.46% | 4.31% | 4.80% | 4.34% | 4.97% | 4.63% | 5.15% | 5.05% |
| 65 to 74 years | 6.32% | 6.10% | 6.42% | 6.04% | 6.62% | 6.10% | 6.77% | 6.26% |
| 75 to 84 years | 4.36% | 3.77% | 4.32% | 3.72% | 4.28% | 3.84% | 4.28% | 3.67% |
| 85 years and over | 1.77% | 1.22% | 1.83% | 1.13% | 1.88% | 1.21% | 1.83% | 1.18% |
| Median age (years) | 36.4 | 34 | 36.6 | 34 | 36.8 | 34 | 36.8 | 35 |
| | | | | | | | | |
| 18 years and over | 75.37% | 72.39% | 75.50% | 71.85% | 75.68% | 72.68% | 75.72% | 72.36% |
| 21 years and over | 71.18% | 68.36% | 71.31% | 67.86% | 71.43% | 68.61% | 71.41% | 68.34% |
| 62 years and over | 15.08% | 13.48% | 15.24% | 13.25% | 15.41% | 13.57% | 15.79% | 14.00% |
| 65 years and over | 12.45% | 11.09% | 12.56% | 10.89% | 12.78% | 11.15% | 12.89% | 11.11% |
| | | | | | | | | |
| 18 years and over | 75.37% | 72.39% | 75.50% | 71.85% | 75.68% | 72.68% | 75.72% | 72.36% |
| Male | 36.67% | 34.25% | 36.75% | 33.89% | 36.86% | 34.33% | 36.91% | 34.04% |
| Female | 38.71% | 38.14% | 38.75% | 37.96% | 38.82% | 38.35% | 38.81% | 38.32% |
| | | | | | | | | |
| 65 years and over | 12.45% | 11.09% | 12.56% | 10.89% | 12.78% | 11.15% | 12.89% | 11.11% |
| Male | 5.23% | 4.80% | 5.30% | 4.73% | 5.41% | 4.77% | 5.48% | 4.90% |
| Female | 7.22% | 6.29% | 7.26% | 6.16% | 7.37% | 6.38% | 7.41% | 6.20% |
| **RACE** | | | | | | | | |
| White | 80.08% | 66.94% | 79.96% | 67.29% | 79.80% | 66.62% | 79.57% | 66.15% |
| Black or African American | 12.81% | 16.18% | 12.85% | 15.51% | 12.85% | 15.59% | 12.91% | 15.75% |
| American Indian and Alaska Native | 0.97% | 0.89% | 0.97% | 1.16% | 1.01% | 1.10% | 1.03% | 0.81% |
| Asian | 4.40% | 6.35% | 4.43% | 5.88% | 4.46% | 6.30% | 4.56% | 6.41% |
| **HISPANIC OR** | | | | | | | | |
| Hispanic or Latino (of any race) | 14.80% | 23.59% | 15.09% | 24.64% | 15.44% | 23.85% | 15.77% | 25.34% |
| Not Hispanic or Latino Total | 85.20% | 76.41% | 84.91% | 75.36% | 84.56% | 76.15% | 84.23% | 74.66% |

## APPENDIX B

# VARIABLES DESCRIPTION AND SOURCE

| ***DEPENDENT VARIABLES*** | ***DESCRIPTION AND SOURCE*** |
|---|---|
| *Wireline* | This variable is dichotomous, taking on a value of 1 if the surveyed household subscribed to wireline telephone service at the time of the survey, and is zero otherwise. |
| | Source: National Health Interview Survey, annual, 2003-2010. |
| *Wireless* | This variable is dichotomous, taking on a value of 1 if the surveyed household subscribes to wireless telephone service at the time of the survey, and is zero otherwise. |
| | Source: National Health Interview Survey, annual, 2003-2010. |
| ***NODAL VARIABLES*** | ***DESCRIPTION AND SOURCE*** |
| *Retired Household* | This variable is dichotomous, taking on a value of 1 if surveyed household includes retired person |
| | Source: National Health Interview Survey, annual, 2003-2010. |
| *Housewife* | This variable is dichotomous, taking on a value of 1 if surveyed household includes member who keeps the house |
| | Source: National Health Interview Survey, annual, 2003-2010. |
| *Part-Time Employed* | This variable is dichotomous, taking on a value of 1 if someone in surveyed household works 20 hours or less |
| | Source: National Health Interview Survey, annual, 2003-2010. |
| *Limited Youth* | This variable is dichotomous, taking on a value of 1 if surveyed household includes member who has health limitations and under age 31 |
| *Limited Adult* | This variable is dichotomous, taking on a value of 1 if surveyed household includes member who has health limitations and above age 30 |
| | Source: National Health Interview Survey, annual, 2003-2010. |
| *Young Household* | This variable is dichotomous, taking on a value of 1 if all members of surveyed household are under age 31 |
| *Young-Middle Household* | This variable is dichotomous, taking on a value of 1 if all members of surveyed household are between ages 31 and 44 |
| *Older-Middle Household* | This variable is dichotomous, taking on a value of 1 if all members of surveyed household are between ages 45 and 64 |
| *Older Household* | This variable is dichotomous, taking on a value of 1 if all members of surveyed household are above age 65 |
| | Source: National Health Interview Survey, annual, 2003-2010. |
| *Wealthy Retired Household* | This variable is dichotomous, taking on a value of 1 if all members of surveyed household are above age 65 and have ratio of family income to poverty threshold above 4 |
| | Source: National Health Interview Survey, annual, 2003-2010. |
| *Unrelated Adults* | This variable is dichotomous, taking on a value of 1 if surveyed household includes only unrelated adults |
| | Source: National Health Interview Survey, annual, 2003-2010. |
| *Children* | This variable is dichotomous, taking on a value of 1 if surveyed household includes member under age 18 |
| | Source: National Health Interview Survey, annual, 2003-2010. |
| *Student* | This variable is dichotomous, taking on a value of 1 if surveyed household includes students |
| | Source: National Health Interview Survey, annual, 2003-2010. |
| *Own House* | This variable is dichotomous, taking on a value of 1 if someone in surveyed household owns the home |
| | Source: National Health Interview Survey, annual, 2003-2010. |
| *Ratio Working* | Ratio of people in the surveyed household who work |
| | Source: National Health Interview Survey, annual, 2003-2010. |
| ***DEMOGRAPHIC VARIABLES*** | ***DESCRIPTION AND SOURCE*** |

| | |
|---|---|
| *Female Household* | This variable is dichotomous, taking on a value of 1 if the surveyed household includes only females, and is zero otherwise. |
| | Source: National Health Interview Survey, annual, 2003-2010. |
| *Male Household* | This variable is dichotomous, taking on a value of 1 if the surveyed household includes only males, and is zero otherwise. |
| | Source: National Health Interview Survey, annual, 2003-2010. |
| *White* | This variable is dichotomous, taking on a value of 1 if the surveyed household consists of white people only, and is zero otherwise. |
| *Black* | This variable is dichotomous, taking on a value of 1 if the surveyed household consists of Black/African American people only, and is zero otherwise. |
| *Hispanic* | This variable is dichotomous, taking on a value of 1 if the surveyed household consists of Hispanic people only, and is zero otherwise. |
| *Asian* | This variable is dichotomous, taking on a value of 1 if the surveyed household consists of Asian people only, and is zero otherwise. |
| *Indian* | This variable is dichotomous, taking on a value of 1 if the surveyed household consists of Indian people only, and is zero otherwise. |
| *Chinese* | This variable is dichotomous, taking on a value of 1 if the surveyed household consists of Chinese people only, and is zero otherwise. |
| | Source: National Health Interview Survey, annual, 2003-2010. |
| *Divorced* | This variable is dichotomous, taking on a value of 1 if surveyed household includes divorced member |
| | Source: National Health Interview Survey, annual, 2003-2010. |
| *Population Density* | Population density, county level. |
| | Source: U.S. Census Bureau, annual 2003-2010 |
| ***PRICE AND INCOME VARIABLES*** | ***DESCRIPTION AND SOURCE*** |
| *Wireline Price* | *As discribed in the text, see p.11* |
| | Source: data was supplied by Greg Rosston, Scott Savage and Breadley Wimmer, who collected it for the purposes of the research in Rosston, Savage and Wimmer (2008), adjusted for years 2003-2009 |
| *Wireless Price* | As discribed in the text, see p. 12 |
| | Source: CTIA's Wireless Industry Report Indices, 2008 |
| *CPI for Wireless Telephone Services* | Consumer price index for wireless telephone services |
| | Source: FCC "Reference Book of Rates, Price Indices, and Household Expenditures for Telephone Service", annual |
| *CPI for Wireline Telephone Services* | Consumer price index for wireline telephone services |
| | Source: FCC "Reference Book of Rates, Price Indices, and Household Expenditures for Telephone Service", annual |
| *State and Local Taxes on Wireless Telephony* | As discribed in the text, see p. 12 |
| | Source: The Council on State Taxation (COST), years 2001, 2004, 2007, 2010 |
| *Income1* | This variable is dichotomous, taking on a value of 1 if the surveyed household has family income below the poverty threshold |
| *Income2* | This variable is dichotomous, taking on a value of 1 if the surveyed household has a ratio of family income to poverty threshold between 1 and 2 |
| *Income3* | This variable is dichotomous, taking on a value of 1 if the surveyed household has a ratio of family income to poverty threshold between 2 and 4 |
| *Income4* | This variable is dichotomous, taking on a value of 1 if the surveyed household a has ratio of family income to poverty threshold is above 4 |
| | Source: National Health Interview Survey, annual, 2003-2010. |
| ***QUALITY VARIABLES*** | ***DESCRIPTION AND SOURCE*** |
| *Mountainous* | Land Surface Form Typography code, ranges from 1 to 21. Higher value indicates more mountainous surface. |
| | Source: U.S. Department of Agriculture, Area Resource File, http://www.ers.usda.gov/Data/NaturalAmenities/ |

| | |
|---|---|
| *Water* | Percent water area in the county |
| | Source: U.S. Department of Agriculture, Area Resource File, http://www.ers.usda.gov/Data/NaturalAmenities/ |
| *Cellsites* | Number of registered cellsites |
| | Source: CTIA's Wireless Industry Report Indices, annual |
| *Wireline Broadband* | Number of residential connections over 200 kbps in at least one direction, by state |
| | Source: FCC Internet Access Services Report, 2004-2011 |
| ***EXCLUSION RESTRICTIONS*** | ***DESCRIPTION AND SOURCE*** |
| *Telecommunications Wages* | Mean annual wage for Telecommunications Equipment and Line Installers and Repairers |
| | Source: Bureau of Labor Statistics, Department of Labor, 2003-2010 |
| *Mobile Penetration* | Mobile wireless services penetration rate in a county |
| | Source: National Health Interview Survey, annual, 2003-2010. |

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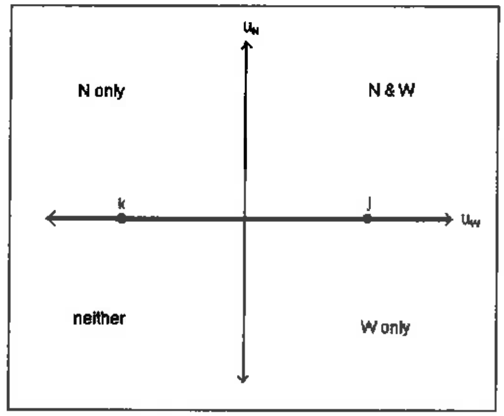
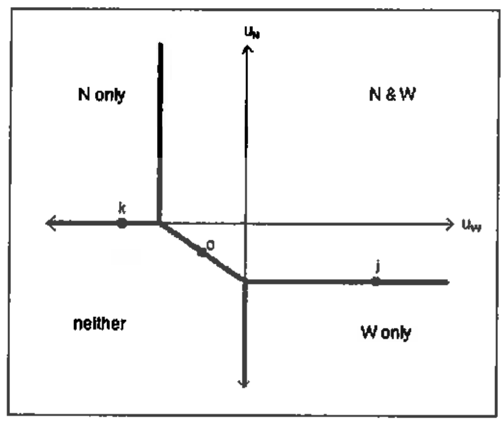
FIGURE 1
WIRELINE AND WIRELESS SERVICES

**Panel a: Independent Services, Γ = 0**




**Panel b: Complementary Services, Γ > 0**




**Panel c: Substitute Services, Γ < 0**

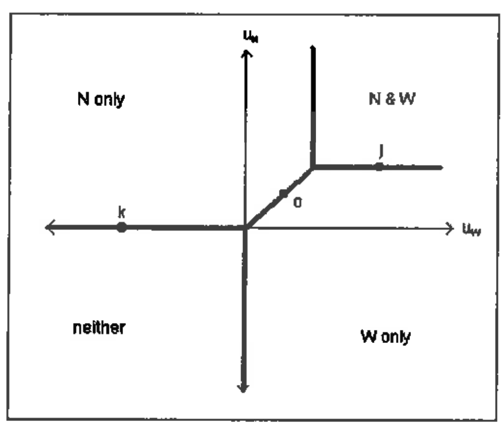


FIGURE 2
HOUSEHOLDS WITH WIRELINE, WIRELESS, BOTH OR NONE
2003-2010

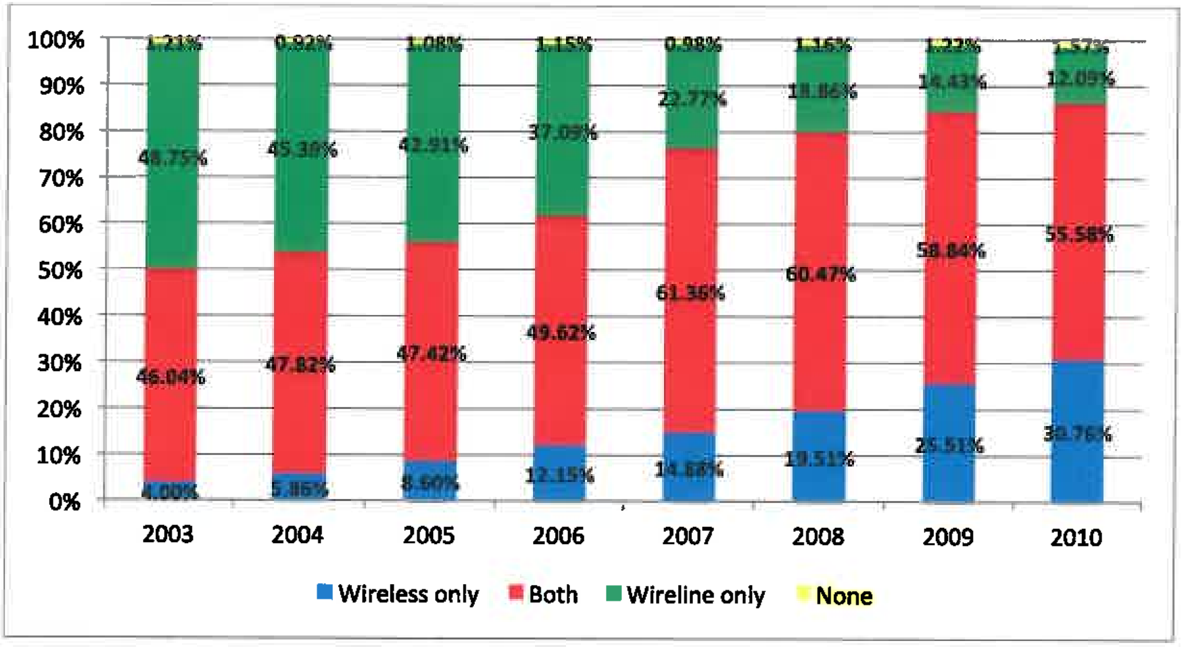



FIGURE 3
HOUSEHOLDS WITH WIRELINE, WIRELESS, BOTH OR NONE
AMONG HOUSEHOLDS BELOW POVERTY THRESHOLD
2003-2010

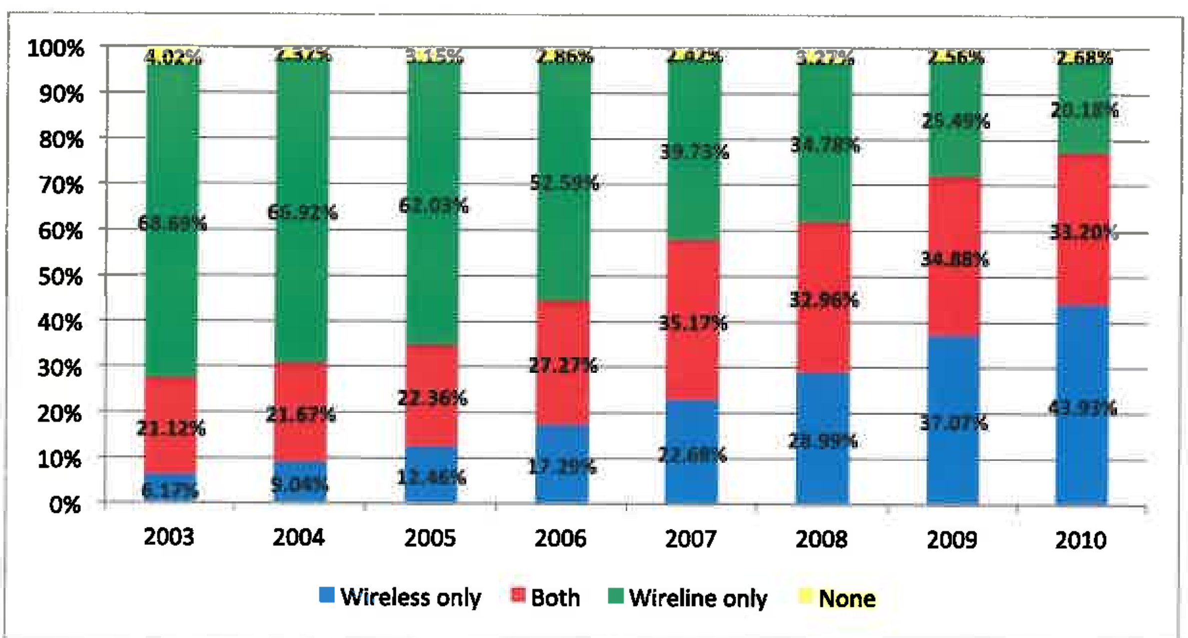
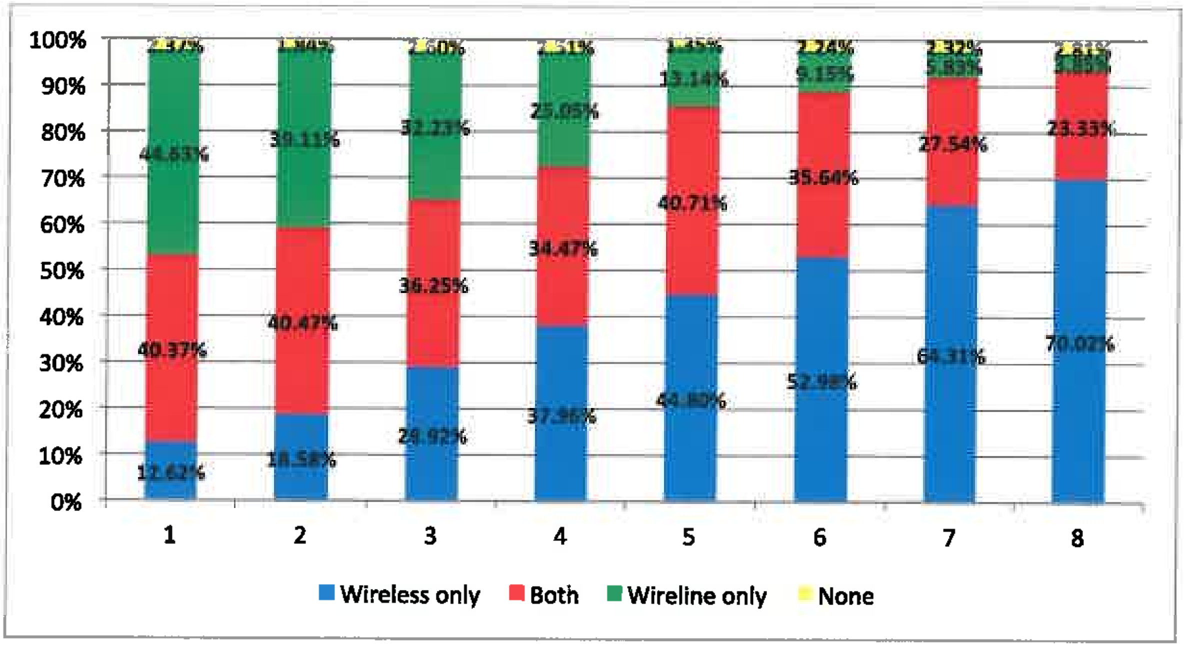


FIGURE 4
HOUSEHOLDS WITH WIRELINE, WIRELESS, BOTH OR NONE
AMONG HOUSEHOLDS WITH ALL MEMBERS UNDER AGE 31
2003-2010



## TABLE 1
## WIRELINE AND WIRELESS CONSUMPTION

| Whole Sample | | |
|---|---|---|
| Phone | Frequency | Percent |
| None | 2,228 | 1.18% |
| Wireline Only | 56,141 | 29.61% |
| Wireless Only | 29,831 | 15.73% |
| Both | 101,416 | 53.48% |
| Whole Sample | 189,616 | 100.00% |

## TABLE 2
## TETRACHORIC AND PARTIAL CORRELATIONS FOR WIRELINE AND WIRELESS CONSUMPTION

| | Tetrachoric Correlation | Partial correlation |
|---|---|---|
| Full Sample | -0.5328* | -0.3720* |
| Year 2003 | -0.3384* | 0.0507* |
| Year 2004 | -0.4651* | -0.0562* |
| Year 2005 | -0.5196* | -0.1343* |
| Year 2006 | -0.5457* | -0.2001* |
| Year 2007 | -0.4519* | -0.138 |
| Year 2008 | -0.4452* | -0.1798* |
| Year 2009 | -0.4433* | -0.1888* |
| Year 2010 | -0.4098* | -0.2268* |
| Income1 | -0.7187* | -0.6631* |
| Income2 | -0.6836* | -0.6013* |
| Income3 | -0.5724* | -0.4864* |
| Income4 | -0.3859* | -0.4164* |

*Significant at 1 percent.

## TABLE 3
## PARAMETER ESTIMATES FOR PROBIT AND BIVARIATE PROBIT MODELS

| | Model (a) | | Model (b) | | Model (c) | |
|---|---|---|---|---|---|---|
| | Probit | | Bivariate probit | | Recursive Bivariate probit | |
| **VARIABLES** | *wireline* | *wireless* | *wireline* | *wireless* | *wireline* | *wireless* |
| *Wireless* | | | | | -1.087*** | |
| | | | | | (0.0328) | |
| ***Price*** | | | | | | |
| *Wireline Price* | -0.0134* | 0.0372*** | -0.0101 | 0.0367*** | 0.0374*** | 1.633*** |
| | (0.00748) | (0.00607) | (0.00743) | (0.00606) | (0.01280) | (0.00914) |
| *Wireless Price* | 0.0849*** | -0.0611*** | 0.0826*** | -0.0611*** | 0.0351*** | -0.755*** |
| | (0.00376) | (0.00295) | (0.00373) | (0.00294) | (0.00641) | (0.00489) |
| ***Income*** | | | | | | |
| *Income2* | -0.0108 | 0.242*** | -0.00989 | 0.240*** | 0.105*** | 1.703*** |
| | (0.01480) | (0.01230) | (0.01480) | (0.01230) | (0.01900) | (0.01570) |
| *Income3* | 0.137*** | 0.550*** | 0.120*** | 0.546*** | 0.317*** | 1.560*** |
| | (0.01380) | (0.01170) | (0.01380) | (0.01170) | (0.01780) | (0.01480) |
| *Income4* | 0.369*** | 0.859*** | 0.342*** | 0.849*** | 0.565*** | 0.517*** |
| | (0.01530) | (0.01340) | (0.01530) | (0.01340) | (0.01610) | (0.01550) |
| ***Nodal*** | | | | | | |
| *Retired Household* | 0.465*** | -0.168*** | 0.439*** | -0.170*** | 0.486*** | 2.782*** |
| | (0.02650) | (0.01820) | (0.02590) | (0.01820) | (0.03170) | (0.02360) |
| *Young Household* | -0.793*** | 0.432*** | -0.795*** | 0.443*** | -0.710*** | 1.175*** |
| | (0.01240) | (0.01230) | (0.01240) | (0.01230) | (0.01520) | (0.01510) |
| *Young-Middle Household* | -0.398*** | 0.264*** | -0.411*** | 0.266*** | -0.333*** | 1.436*** |
| | (0.01790) | (0.01640) | (0.01780) | (0.01640) | (0.02070) | (0.02020) |
| *Older-Middle Household* | 0.0753*** | 0.0751*** | 0.0530*** | 0.0684*** | 0.116*** | 1.627*** |
| | (0.01660) | (0.01290) | (0.01650) | (0.01290) | (0.02000) | (0.01650) |
| *Student* | -0.0786*** | 0.318*** | -0.0617*** | 0.313*** | 0.0549** | 1.864*** |
| | (0.01990) | (0.01810) | (0.02000) | (0.01800) | (0.02400) | (0.02240) |
| *Housewife* | 0.0242 | -0.00908 | 0.0129 | -0.00926 | 0.0476*** | 1.125*** |
| | (0.01520) | (0.01180) | (0.01500) | (0.01170) | (0.01720) | (0.01460) |
| *Part-Time Employed* | 0.146*** | 0.129*** | 0.142*** | 0.127*** | 0.168*** | -0.214*** |
| | (0.01340) | (0.01160) | (0.01330) | (0.01160) | (0.01390) | (0.01390) |
| *Ratio Working* | -0.439*** | 0.397*** | -0.423*** | 0.399*** | -0.262*** | 3.262*** |
| | (0.02240) | (0.01750) | (0.02200) | (0.01750) | (0.03140) | (0.02380) |
| *Limited Youth* | 0.000195 | 0.109*** | -0.00185 | 0.108*** | 0.0302* | 0.113*** |
| | (0.01510) | (0.01270) | (0.01490) | (0.01260) | (0.01550) | (0.01530) |
| *Limited Adult* | 0.0877*** | -0.0501*** | 0.0860*** | -0.0495*** | 0.0913*** | 1.187*** |
| | (0.01570) | (0.01130) | (0.01540) | (0.01130) | (0.01760) | (0.01410) |
| *Own House* | 0.538*** | 0.101*** | 0.528*** | 0.0941*** | 0.604*** | 1.043*** |
| | (0.01040) | (0.00895) | (0.01040) | (0.00897) | (0.01250) | (0.01130) |
| *Children* | -0.125*** | 0.404*** | -0.136*** | 0.398*** | 0.0232 | 3.037*** |
| | (0.01950) | (0.01580) | (0.01940) | (0.01580) | (0.02810) | (0.02170) |
| *Wealthy Retired Household* | -0.156*** | 0.204*** | -0.150*** | 0.209*** | -0.0795** | -0.0428* |
| | (0.03470) | (0.01900) | (0.03470) | (0.01900) | (0.03570) | (0.02260) |
| *Population Density* | 4.21e-06** | -1.25e-05*** | 3.51e-06* | -1.24e-05*** | -7.39e-06** | -0.000381*** |
| | (0.00000) | (0.00000) | (0.00000) | (0.00000) | (0.00000) | (0.00000) |
| ***Quality controls*** | | | | | | |
| *Wireline Broadband* | 1.219*** | -0.374*** | 1.157*** | -0.395*** | 0.695*** | -18.73*** |
| | (0.09780) | (0.07870) | (0.09700) | (0.07880) | (0.15500) | (0.11600) |
| *Cellsites* | -2.19e-05*** | 1.41e-05*** | -2.13e-05*** | 1.42e-05*** | -1.68e-05*** | 0.000150*** |
| | (0.00000) | (0.00000) | (0.00000) | (0.00000) | (0.00000) | (0.00000) |
| *Wireline Price Residual* | 0.00702 | -0.0304*** | 0.00371 | -0.0299*** | -0.0426*** | -1.631*** |
| | (0.00750) | (0.00609) | (0.00745) | (0.00608) | (0.01280) | (0.00914) |
| *Wireless Price Residual* | -0.0519*** | 0.0391*** | -0.0508*** | 0.0390*** | -0.0228*** | 0.776*** |
| | (0.00387) | (0.00304) | (0.00385) | (0.00303) | (0.00631) | (0.00454) |
| ***Rho (ρ)*** | | | | -0.523*** | | 0.0784*** |
| | | | | (0.00750) | | (0.01980) |
| ***Demographic controls*** | yes | yes | yes | yes | yes | yes |
| ***Other quality controls*** | yes | yes | yes | yes | yes | yes |
| ***Constant*** | | | | | 1.887*** | -4.394*** |
| | | | | | -0.175 | -0.144 |
| *Observations* | 185,911 | 185,911 | 185,911 | 185,911 | 185,911 | 185,911 |

***Significant at 10 percent**
****Significant at 5 percent**

***Significant at 1 percent.

## TABLE 4
## MARGINAL PRICE AND INCOME EFFECTS ON CONSUMER CHOICES

| | *Wireline* | *Wireless* |
|---|---|---|
| *Own* | $(\partial Q_N/\partial P_N) = -.0019$*** | $(\partial Q_W/\partial P_W) = -.0204$*** |
| *Cross* | $(\partial Q_N/\partial P_W) = .0152$*** | $(\partial Q_W/\partial P_N) = .0122$*** |
| *Change from Income1 to Income4* | $Q_N^{Income4} - Q_N^{Income1} =$ .0595*** | $Q_W^{Income4} - Q_W^{Income1} =$ .2577*** |

***Significant at 1 percent.

## TABLE 5
## THE EVOLUTION OF CONSUMER SUBSTITUTION PATTERNS

| | |
|---|---|
| **N**<br>$(\partial \pi_N/\partial P_N)_{03\text{-}06} = -.0982$***<br>$(\partial \pi_N/\partial P_N)_{07\text{-}10} = -.0588$*** | **NW**<br>$(\partial \pi_{NW}/\partial P_N)_{03\text{-}06} = .0476$***<br>$(\partial \pi_{NW}/\partial P_N)_{07\text{-}10} = .01168$*** |
| **Off-the-grid*** | **W**<br>$(\partial \pi_W/\partial P_N)_{03\text{-}06} = .0471$***<br>$(\partial \pi_W/\partial P_N)_{07\text{-}10} = .0489$*** |

*The marginal impact of wireline prices on the likelihood of consumers shifting to the "off the grid" category is estimated to be essentially zero and is not shown here.
***Significant at 1 percent.

# TABLE 6
# PARAMETER ESTIMATES FOR ALTERNATIVE-SPECIFIC CONDITIONAL LOGIT MODEL

| ***VARIABLES*** | ***None*** | ***Wireless*** | ***Both*** |
|---|---|---|---|
| ***Price*** | -0.0139*** | -0.0139*** | -0.0139*** |
| | (0.0034) | (0.0034) | (0.0034) |
| ***Income*** | | | |
| *Income2* | -0.250** | 0.171*** | 0.389*** |
| | (0.1262) | (0.0494) | (0.0392) |
| *Income3* | -0.419*** | 0.363*** | 1.009*** |
| | (0.1297) | (0.0514) | (0.0426) |
| *Income4* | -0.494*** | 0.507*** | 1.686*** |
| | (0.1532) | (0.0598) | (0.0475) |
| ***Nodal*** | | | |
| *Retired Household* | -0.982*** | -1.423*** | -0.328*** |
| | (0.1950) | (0.0999) | (0.0485) |
| *Young Household* | 0.916*** | 1.564*** | 0.340*** |
| | (0.1164) | (0.0546) | (0.0467) |
| *Young-Middle Household* | 0.626*** | 0.788*** | 0.322*** |
| | (0.1797) | (0.0753) | (0.0611) |
| *Older-Middle Household* | 0.128 | -0.224*** | 0.129*** |
| | (0.1569) | (0.0654) | (0.0419) |
| *Student* | -0.206 | 0.378*** | 0.430*** |
| | (0.2179) | (0.0756) | (0.0609) |
| *Housewife* | -0.199* | -0.270*** | -0.0845*** |
| | (0.1387) | (0.0565) | (0.0354) |
| *Part-Time Employed* | -0.321 | -0.0628 | 0.260*** |
| | (0.1668) | (0.0577) | (0.0417) |
| *Ratio Working* | 0.0480 | 0.853*** | 0.369*** |
| | (0.1736) | (0.0757) | (0.0489) |
| *Limited Youth* | -0.115 | 0.114** | 0.192*** |
| | (0.1722) | (0.0555) | (0.0435) |
| *Limited Adult* | -0.267** | -0.341*** | -0.133*** |
| | (0.1414) | (0.0605) | (0.0387) |
| *Own House* | -0.674*** | -0.762*** | 0.321*** |
| | (0.1062) | (0.0407) | (0.0272) |
| *Children* | 0.0747 | 0.378*** | 0.579*** |
| | (0.1617) | (0.0598) | (0.0453) |
| *Wealthy Retired Household* | 0.270 | 0.251* | 0.197*** |
| | (0.4056) | (0.1698) | (0.0669) |
| *Population Density* | -1.28e-05** | -2.50e- | -8.56e- |
| | (0.0000) | (0.0000) | (0.0000) |
| ***Quality controls*** | | 0 | |
| *Wireline Broadband* | 1.368*** | 0.0722 | 0.823*** |
| | (0.3496) | (0.1485) | (0.1184) |
| *Cellsites* | 6.71e-06** | 3.90e- | 1.14e- |
| | (0.0000) | (0.0000) | (0.0000) |
| *Wireline Price Residual* | -0.0171** | -0.00876** | -0.00357** |
| | (0.0082) | (0.0045) | (0.0018) |
| *Wireless Price Residual* | -0.0451** | 0.000855 | 0.0182*** |
| | (0.0230) | (0.0085) | (0.0060) |
| ***Demographic controls*** | yes | yes | yes |
| ***Other Quality Controls*** | yes | yes | yes |
| ***Constant*** | -4.607*** | -8.503*** | -2.737*** |
| | (0.6472) | (0.3638) | (0.3175) |
| *Observations* | 748,128 | 748,128 | 748,128 |

***Significant at 10 percent**
****Significant at 5 percent**
*****Significant at 1 percent.**