Estimating Demand for Cellular Phone Service under Nonlinear Pricing

Ching-I Huang[1]

Department of Economics, National Taiwan University

Abstract

Cellular phone carriers typically offer complicated nonlinear tariffs. Consumers make a discrete choice among several rate plans. Each plan has a nonlinear price schedule, and price is usually lower for intra-network calls. Intra-network discounts reduce the compatibility among different carriers. I present an empirical framework to estimate demand under such nonlinear price schemes and evaluate the impact of intra-network discounts on the market structure. I apply the method to analyze the cellular phone service market in Taiwan. While intra-network discounts increase consumer surplus modestly, there are considerable tipping effects on the market shares.

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1 Introduction

In a competitive cellular phone service market, each carrier operates a different network. A customer of one network can make a phone call to a customer in another network whenever these two networks are interconnected. Interconnection essentially makes the cellular service of one carrier compatible with others. Firms, however, can reduce compatibility by their pricing strategies.

Cellular carriers generally offer several rate plans at the same time. The price schedule differs across rate plans. Consumers select one of the rate plans if they want to use cellular phone service. Furthermore, the price schedule under a rate plan is typically nonlinear in quantity. A rate plan usually involves a fixed subscription fee and unit prices, which depend on both the total volume and the termination location of a phone call. The price of a call terminated within the caller's network is generally lower than the price of a call terminated in other networks. The intra-network discounts reduce compatibility among different networks. As a result, consumers would prefer a large network for any given price schedule. Theoretical results of such termination-based price discrimination are sensitive to model specifications [2]. The effect of nonlinear pricing is an empirical issue.

To capture the impact of the entire nonlinear price schedule on consumer behavior, I propose a preference-based structural model, which is conceptually similar to Miravete (2002). Consumers are heterogeneous in their marginal utility of making phone calls, which is determined by their initial taste types and interim random shocks. The initial taste type is known prior to the subscription decision and is private information. This asymmetric information induces firms to screen consumers by providing a menu of rate plans. After consumers subscribe to a rate plan, there are carrier-level shocks on signal quality and consumer-level shocks on taste. Both types of shocks affect the marginal utility of cellular service. Consumers choose the volume that maximizes their utility, taking into account the realized interim shocks. But because only the distribution of the interim shocks, not the realized values, is known at the subscription stage, consumers select a rate plan according to their expected utility. Standard nonlinear tariff theory ignores the time lag between the subscription decision and the volume choice, implying that the effective price scheme is the lower envelope of all price schedules in the available rate plans. In the telephone industry, however, the

[2] For example, see Laffont et al. (1998), Gans and King (2001).

expected usage at the moment of subscription decision could differ from the actual usage because of the temporal separation. Therefore, the actual payment could be above the lower envelope.

I analyze consumer demand by combining monthly carrier-level aggregate output data with cross-sectional expenditure survey data. The market share of a carrier can be measured in two different ways, either by the number of its subscribers or by the total traffic volume. The first measure of market shares allows me to identify the discrete plan choice while the second measure identifies consumers' volume choice, which is decided after observing interim shocks. Variation in signal quality is inferred from the difference between the two measures. Furthermore, I incorporate the expenditure distribution among consumers to identify their vertically heterogeneous tastes of cellular phone service and link the consumption behavior with their demographic variables. In my proposed estimation framework, I construct moment conditions from both data sources. These moment conditions are jointly used as constraints in the maximum likelihood estimation to obtain parameters in the behavior model.

I apply the model to the cellular phone service market in Taiwan, where intra-network discounts are large and common since the deregulation in 1998. The carrier of a phone number can be easily recognized from its prefix. Therefore, callers are aware of the discounts whenever they dial an intra-network phone number. This feature allows consumers to make different volume choices based on the termination of a phone call.

I find significant heterogeneities on the taste of cellular service among consumers. For a given quantity of service, the standard deviation of marginal utility among consumers is 0.0732 Taiwan dollars per second.[3] Income variation can explain 9.79% of the taste variation. On the supply side, carriers are vertically differentiated in two aspects. First, carriers differ in their attractiveness at the subscription stage conditional on the expected surplus associated with calling. The value of the difference between the highest carrier and the lowest one is 590 Taiwan dollars a month. Second, carriers have different perceived signal qualities which affect the volume choices. The marginal utility of the highest quality carrier is higher than the lowest quality carrier by 0.1483 Taiwan dollars per second.

[3]As a comparison, the marginal prices range between 0 and 0.2227 Taiwan dollars per second.

Termination-based price discrimination is an effective tool to alter the market structure. By performing a counterfactual simulation to the market in December 2003, I find that the number of subscribers in the largest network would decrease 43% while the number in the smallest one would increase 39% if intra-network discounts were eliminated. During my research period (May 2000 – June 2005), the Herfindahl-Hirschman Index (HHI) has, on average, increased 264 points in this highly concentrated market due to intra-network discounts. Furthermore, the ability to recognize the carrier of a phone number has enhanced the "tipping effects" of intra-network discounts on the market structure, but it has only accounted for 33 points of the increase in the HHI.

The rest of the paper is organized as follows. In the next section, I discuss the related literature. I then provide a brief background of the industry and describe the data. I present my demand model in Section 4, followed by a discussion of estimation procedure and identification. I describe the empirical results in Section 6 and conclude in the final section.

2 Related Literature

Because firms usually offer a collection of optional rate plans in the telecommunication market, a consumer needs to make a discrete choice over rate plans, followed by a continuous choice of the volume.[4] Train, McFadden, and Ben-Akiva (1987) estimate a nested logit model in which plan choice and volume choice are simultaneous, and both are discrete. Hanemann (1984) provides a framework to estimate discrete/continuous models in which the discrete and continuous choices are linked by the same utility maximization problem. This framework can be used to analyze the simultaneous choices of brand and quantity, but does not account for the time lag between plan choice and volume choice. Miravete (2002) points out the importance of this time lag. His theoretical model provides a justification for a carrier to offer several rate plans with a nonlinear price schedule. He examines experimental data from a local telephone company in two cities in Kentucky. He concludes that the asymmetry of information between the firm and the consumers about both initial types and interim shocks is significant. The monopoly uses a menu of optional

[4]Some earlier studies on cellular phone demand abstract away the volume choice by assuming all subscribers make the same amount of phone calls. (Parker and Röller, 1997; Hausman, 1997)

calling plans to screen consumers with respect to the initial types and nonlinear price schedule within each plan to screen them with respect to the interim demand shocks.

My model is close to that of Narayanan, Chintagunta, and Miravete (2005), who analyze demand for local telephone service. As in my model, they assume that interim shocks are observed after the plan choice. They use subscriber-level data on consumption choices to obtain model parameters, while my data are more aggregate. Economides, Seim, and Viard (2005) study local phone service in a competitive environment using phone bill information from a survey of residential customers in New York State. The moment conditions from the plan choice and from the volume choice are jointly estimated. However, they do not explicitly account for time separation between the plan choice and the volume choice. Similarly, Iyengar (2004) uses subscriber-level billing records from a cellular phone carrier to study demand for wireless service. The difference between ex-ante optimal volume and ex-post actual volume is modelled as white noise, independent of other variables. In my framework, the difference results from interim shocks, and the effect of random shocks on volume depends on both the initial consumer type and the price schedule of the chosen rate plan.

Berry, Levinsohn, and Pakes (1995) propose a parsimonious empirical approach to analyze discrete choice with heterogeneous consumers using brand-level aggregate data. They recover the average utility level of each product from observed market shares. In their model, there is no quantity choice. Consumers are assumed to purchase a single unit of one product. This is appropriate for the automobile market they study. Their approach has been adapted to study price discrimination with discrete quantity (or quality) choice in Broadway theater (Leslie, 2004), paper towers (Cohen, 2001), and specialty coffee (McManus, 2006). Nonetheless, this approach has to be modified if consumers purchase different quantities and the quantity choice is on a continuous spectrum. The extension of Nair, Dubé, and Chintagunta (2005) accounts for the quantity choice in the refrigerated juice market. As in the discrete/continuous choice model, the discrete brand choice and the continuous quantity choice are linked by specifying the utility function. Different from the telephone service market, consumers make these two choices simultaneously.

To my knowledge, there are very few pervious studies to quantify the effect of intra-network discounts on market demand. By using reduced-form estimation, Kim and Kwon (2003) and Fu

(2004) find that large networks are more attractive to consumers. However, it is difficult to separate the effect of intra-network discounts from other factors such as reputation. By using carrier-level subscription data, Grajek (2003) proposes a structural model to estimate network effects in the Polish mobile phone industry. By comparing the network effects before and after intra-network discounts are eliminated in the market, he finds a significant increase in compatibility between carriers.

3 The Cellular Phone Service in Taiwan

The research period in the empirical part of this study is between May 2000 and June 2005.

3.1 Cellular Carriers

I focus on GSM carriers[5] since they dominate the wireless telephone service in Taiwan. The industry is regulated through licenses by the Directorate General of Telecommunications. During the research period, the number of GSM licences is fixed. The regulator divides Taiwan into North, Central, and South regions.[6] There are four national carriers, Chunghwa Telecom (CHT), Taiwan Cellular (TCC), Far Eastone Telecommunications (FET), and KG Telecommunications (KGT), and two regional carriers, Trans Asia Telecommunications (TAT) and Mo Bi Tai Communications (MBT). See Table 1 for their operational regions and market shares. In addition to the GSM system, there are two other types of wireless telephone systems in Taiwan, PHS and 3G. The number of their subscribers are both less than 4% of the number of GSM subscribers.[7]

[5]GSM (global system for mobile communications) is a digital technology to transmit mobile voice and data. It is one of the second generation wireless systems and is the most widely used technology in the world for mobile telephones.

[6]The counties and cities included in each of the three regions are (1) North Region: Keelung, Taipei, Taoyuan, Hsinchu, Yilan, Hualien, and Lienchiang; (2) Central Region: Miaoli, Taichung, Changhua, Nantou, and Yunlin; (3) South Region: Chiayi , Tainan, Kaohsiung, Pingtung, Taitung, Penghu, and Kinmen. The proportion of the population is 45% in the North Region, 25% in the Central Region, and 30% in the South.

[7]PHS (personal handy-phone system) is generally considered inferior to GSM because of its lower power and smaller coverage area. First International Telecom, which began its PHS service in June 2001, is the only firm operating a PHS system. Its coverage area is limited to some metropolitan areas. 3G stands for the third generation wireless system. Five national 3G licenses were auctioned off by the Directorate General of Telecommunications in January 2002. Three of them were acquired by the incumbent GSM operators, Chunghwa Telecom, Taiwan Cellular, and Far Eastone. An entrant, Asia Pacific Broadband Wireless Communications, launched its 3G service in July 2003. Other carriers did not begin operating 3G service until July 2005.

Table 1: Operational regions and market shares by carrier

	Operational Regions			Market Shares	
Carrier	North	Central	South	by Subscribers	by Volume
Chunghwa Telecom	×	×	×	0.308	0.345
Taiwan Cellular	×	×	×	0.256	0.249
Far Eastone	×	×	×	0.182	0.173
KG Telecommunication	×	×	×	0.148	0.169
Trans Asia			×	0.066	0.044
Mo Bi Tai		×		0.029	0.024

Notes: The market shares are the medians of monthly market shares between May 2000 and June 2005.

Expect for their qualities, the products are essentially identical among these GSM carriers. Since their service is operated on the same wireless technology, consumers can switch between them without purchasing a new handset.[8]

Within the research period, the number of firms operating GSM service has fallen from six to three. Taiwan Cellular acquired a regional carrier, Trans Asia, in May 2001. Far Eastone acquired KG Telecommunications in January 2004. In August 2004, Taiwan Cellular acquired another regional carrier, Mo Bi Tai. Nevertheless, these acquired carriers still operate as a separate brand in the market. In particular, their price schemes are different from the acquiring carriers' price schemes. Furthermore, intra-network discounts apply to phone calls between the acquired network and the acquiring network only in some rate plans.

All cellular phone networks are interconnected with each other. They are also interconnected with other types of telephone services such as landline telephone networks. Therefore, a customer in one network can make a call to a receiver in any other network. Because the carrier of a receiver can be recognized by the caller from the prefix of the phone number, it is easy to make different consumption choices when the price depends on the receiver's network.

[8] In particular, handsets are not locked to a specific carrier. Therefore, handsets are compatible with all GSM carriers.

3.2 Output Data

Carrier-level output data come from *Monthly Statistics of Transportation and Communications* published by the Ministry of Transportation and Communications of the Taiwan government. The Directorate General of Telecommunications requires each GSM operator to report the number of active subscribers and the total volume of calls originated from the carrier every month since May 2000.[9] In addition, the numbers of landline telephone subscribers and digital low-powered cordless phone[10] subscribers are also reported in the monthly statistics. Nevertheless, the Directorate General of Telecommunications did not publicly report the monthly output data of 3G service until March 2006. The number of 3G subscribers is available only in the annual statistics.[11]

3.3 Rate Plans

I collect all of the rate plans offered by GSM carriers during the research period. All carriers publicly announce their current rate plans on their websites. Previous rate plans are obtained through direct contacts and from reports on newspapers and magazines. Among these sources, a consumer magazine *Call: Fashion Communications Magazine* reports the rate plans of all carriers regularly since 2001.

All prices are adjusted to 2001 Taiwan dollars (TWD) using the monthly consumer price index.[12] During the research period, the exchange rate as compared to U.S. dollars (USD) has been between 30.7 TWD and 35.1 TWD per USD.

Table 2 summarizes the number of the rate plans by carrier. National carriers offer the same menu of rate plans regardless the region of a customer. Each carrier provides about 10 rate plans

[9]The volume of Far Eastone in the first two months (May and June, 2000) is substantially higher than that in the following months. I suspect that both incoming calls and outgoing calls were counted in the reported numbers. Therefore, I divide the reported values by two to correct the data. In addition, the volume of Chunghwa Telecom appears to have a one-month lag. I shift this sequence backward by one month.

[10]This category includes PHS and CT2 (the second generation cordless telephony). CT2 is an obsolete system during the research period. Its market share has always been less than 0.2% and keeps decreasing.

[11]The number of 3G subscribers was 111,870 in December 2003 and 459,375 in December 2004, respectively (Directorate Generate of Telecommunications, 2005). The latter number is 2.31% of GSM subscribers.

[12]The price index is published by the Directorate-General of Budget, Accounting and Statistics. The consumer price level is very stable. The index has been between 98.8 and 103.4 during the research period.

Table 2: Number of rate plans by carrier

Carrier	2000	2001	2002	2003	2004	2005
Chunghwa Telecom	5	10	10	10	11	11
Taiwan Cellular	5	9	9	10	9	14
Far Eastone	10	11	7	12	13	16
KG Telecommunications	8	10	9	10	11	8
Trans Asia	8	9	9	10	9	10
Mo Bi Tai	9	7	8	8	8	9

Notes: The numbers on the table are the numbers of rate plans in May of the year.

at a given month. There is a modestly increasing trend in the number of plans as more non-voice services are introduced into the market. In addition to the price of voice service, rate plans are differentiated in the quantity and price of non-voice service.

All rate plans have a structure similar to a two-part tariff. Table 3 presents a typical menu of rate plans. Once subscribing to a rate plan, a positive fixed monthly fee is charged in almost all plans. Consumers only pay for outgoing calls, but not incoming calls. Contrary to a typical two-part tariff, there are distinct marginal prices for intra- and inter-network calls, respectively. In addition, there are generally thresholds in a rate plan such that, for volumes less than the thresholds, the total phone tariff is simply the flat monthly fee. The positive marginal prices are only applied to quantities above the thresholds. There are various forms of the thresholds. Some plans provide *free allowances*, which specify the time length of free usage. The amounts of the free allowance for intra- and inter-network calls can be either combined or separated, depending on the plan design. Other plans specify the threshold in the dollar amount, called *deduction.* Only the portion of the usage charge above the deductible amount is counted in the phone bill. Since all plans have only very limited off-peak discounts, I ignore off-peak rates. This simplification causes an upward bias of the price.

Most rate plans charge a lower price for calls terminated within the own network. As Table 4 shows, intra-network prices are close to 50% of inter-network prices. The significant price differences between intra- and inter-network calls provide consumers incentives to identify the carrier of the

Table 3: Rate plans of Taiwan Cellular (January 2004)

Unit: TWD

	Monthly	Deduction	Intra-Network Calls			Regular Calls	
Rate Plan	Fee	Amount	Peak	Off-Peak	Special	Peak	Off-Peak
Plan 1500	1500	1500	0.05/sec		0.015/sec	0.1/sec	
Plan 900	900	900	0.06/sec		0.015/sec	0.11/sec	
Plan 600	600	600	0.07/sec		0.015/sec	0.12/sec	
Plan A1	600	0	3/min	2/min	0.06/min	4/min	3/min
Plan A2	600	0	0.05/sec	0.03/sec	0.015/sec	0.1/sec	0.05/sec
Plan 300	300	300	0.08/sec		0.015/sec	0.13/sec	
Plan 200	200	200	0.08/sec		0.015/sec	0.15/sec	
Plan 66	66	66	0.1/sec		0.015/sec	0.2/sec	
Pre-Paid	0	0	0.1/sec		0.1/sec	0.22/sec	0.12/sec

Peak hours: 08:00 - 23:00 Mon - Fri, 08:00 - 12:00 Sat
Off-peak hours: 23:00 - 08:00 Mon - Fri, 12:00 Sat - 08:00 Mon
Special rate: 01:00 - 07:00 daily

Note: Additional free airtime of 300 seconds is included in Plan 66.

Table 4: Average intra-network discounts by carrier

Carrier	2000	2001	2002	2003	2004	2005
Chunghwa Telecom	0.466	0.441	0.441	0.441	0.468	0.468
Taiwan Cellular	0.373	0.463	0.463	0.440	0.463	0.483
Far Eastone	0.468	0.475	0.469	0.587	0.572	0.562
KG Telecommunications	0.515	0.497	0.534	0.527	0.514	0.469
Trans Asia	0.437	0.437	0.500	0.450	0.389	0.377
Mo Bi Tai	0.298	0.422	0.452	0.369	0.369	0.328

Notes: The discounts are computed from comparing the marginal price of an intra-network call with that of a call terminated in a rival GSM network in May of the year.

receiver while dialing a phone number.

3.4 Consumer Expenditure

The 2002 Survey of Family Income and Expenditure was conducted by the Directorate-General of Budget, Accounting and Statistics. The universal sampling rate is 0.20%, which is 13,681 households. The survey provides information on the number of cellular phones, annual telecommunication expenditure, and annual income at the household level. To account for variation of consumer tastes across regions, household income is used as a proxy to control the differences in socioeconomic status. Based on the survey data, I can obtain the distribution of telecommunication expenditure conditional on income, which will be used in the estimation to identify the heterogeneity of consumer tastes.

4 Behavior Model

My model focuses on the demand of voice service in the cellular industry. The events in a billing period (a month) occur in the following order.

1. Each carrier announces a menu of rate plans. Consumers know their initial taste type.
2. Consumers simultaneously subscribe to one (if any) of the rate plans available in their region. Carriers activate the service for consumers.
3. Random quality shocks for each carrier and random taste shocks for each consumer occur.
4. Consumers make phone calls and pay the tariff.

4.1 The Market Supply

The carriers of cellular phone service, determined by the regulator, vary across the three regions $R \equiv \{North, Central, South\}$. Let K_r denote the set of GSM networks operating in region r. Although some carriers are acquired by others, they still operate as a different network brand in the market.

Rate plans are treated as given by consumers because changes on the plans have to be reported to the regulator and publicly announced before they take effect. For any given carrier, it offers an identical menu of rate plans to all regions where it operates. Denote the set of rate plans offered by network k at time t as P_{kt}. The voice service provided by a carrier is the same regardless the chosen rate plan.

I simplify the tariff formula of plan p at time t to be

$$T_{pt}(q^I, q^O) = MF_{pt} + p^I_{pt} \max\{q^I - a^I_{pt}, 0\} + p^O_{pt} \max\{q^O - a^O_{pt}, 0\}, \tag{1}$$

where q^I and q^O are quantities of intra- and inter-network calls, respectively.[13] A customer faces zero marginal payment when her usage is less than the free allowance ($q^I < a^I_{pt}$, $q^O < a^O_{pt}$). She pays the flat monthly fee MF_{pt}. Beyond the thresholds, the per-second marginal payment is p^I_{pt} for intra-network calls and p^O_{pt} for inter-network calls.

4.2 The Market Demand

Consumers in the market are all individuals in the economy. Let $\mathcal{C}_t$ denote the set of all consumers at time t. $POP_t \equiv |\mathcal{C}_t|$ is the population.[14]

The value of cellular phone service increases in the number of potential receivers. Since all networks are interconnected, the destination of a call can be either in a wireless network or in a landline network. Denote the set of all potential receivers at period t as $\mathcal{D}_t$.

The cost of switching to a different rate plan (regardless the carrier) in the next period is zero in the model.[15] Therefore, consumers make decisions independently over time.

[13]For rate plans with other forms of thresholds, I divide the free allowances into a^I_{pt} and a^O_{pt} in proportion to the respective network sizes. This simplification causes a slightly upward bias of the tariff. In addition, I transform per-minute rates into per-second rates since most plans are based on per-second rates. This transformation lowers the price schedules.

[14]I use the population registration data from the Ministry of the Interior.

[15]There is generally no cost of switching to a different plan within the same carrier. However, the actual cost of switching to another carrier might be positive in the Taiwanese cellular market even though all carriers had reduced the activation fee to zero by 2002. A considerable proportion of customers have a one-year or two-year contract with their carrier in exchange for handset subsidy. In addition, number portability has not taken effect in Taiwan during the research period. The inconvenience of changing a phone number is also part of switching costs.

4.2.1 Consumer Preferences

Consumers are vertically differentiated in their utility of using cellular service. The taste of cellular service depends on a consumer's initial type θ_{it} and interim shock ν_{it}. In addition, it is also affected by the quality shock η_{kt} of her carrier k, which is common to all customers in this network.

The utility of consumer $i \in \mathcal{C}_t$ subscribing to rate plan $p \in P_{kt}$ of network $k \in K_r$ at time t can be expressed as

$$\sum_{j \in \mathcal{D}_{it}} u(x_{ijt}; \theta_{it}, \eta_{kt}, \nu_{it}) - \alpha T_{pt}(\mathbf{x}_{it}) + \delta_{kt} + \varepsilon_{ipt}, \tag{2}$$

where $\mathcal{D}_{it} \subset \mathcal{D}_t$ is a consumer-specific set of receivers, and $\mathbf{x}_{it} \equiv (x_{ijt} : j \in \mathcal{D}_{it})$ is the vector of i's volume choices. The share of each network within $\mathcal{D}_{it}$ is the same as the market share in the entire economy $\mathcal{D}_t$.[16] Let τ_{it} be the size of $\mathcal{D}_{it}$ relative to $\mathcal{D}_t$. $u(x_{ijt}; \theta_{it}, \eta_{kt}, \nu_{it})$ is the utility associated with calling a receiver $j \in \mathcal{D}_{it}$. The utility is additively separable across all receivers in $\mathcal{D}_{it}$. In the second term of (2), $T_{pt}(\mathbf{x}_{it})$ is the total payment of these $\mathbf{x}_{it}$ calls under this rate plan and α is the marginal disutility of payment. Since expenditure on cellular phone services is a small proportion of the household income[17], it is reasonable to consider a quasi-linear model in which consumers are risk-neutral about the phone tariff variation. The third term δ_{kt} is a fixed effect for subscription of network k at time t, which is identical to all consumers. This term includes all carrier characteristics which do not affect the volume choice, such as advertisements, customer service, handset subsidies, value-added services, reputation. The final term ε_{ipt} is consumer i's idiosyncratic preference of plan p. It is i's private information and is independent of other observable variables. Incoming calls do not affect $u(x_{ijt}; \theta_{it}, \eta_{kt}, \nu_{it})$. However, their effects can be captured by the fixed effect δ_{kt}. This implies the utility from incoming calls is identical for any two subscribers in the same network.

Consumer i's utility associated with making x_{ijt} seconds of calls from network k to receiver

[16] This balanced calling pattern is assumed in most theoretical papers, such as Laffont et al. (1998) and Gans and King (2001). Equation (2) would understate the utility of subscribing to regional carriers if the network shares in $\mathcal{D}_{it}$ are the regional market shares instead of national market shares.

[17] The average household expenditure on telecommunications is 1.88% of income in 2002.

$j \in \mathcal{D}_{it}$ at period t is

$$u(x_{ijt}; \theta_{it}, \eta_{kt}, \nu_{it}) = \frac{1}{b} \left(\theta_{it} + \eta_{kt} + \nu_{it} + 1 - \log x_{ijt} \right) x_{ijt}.$$

It depends on the quantity x_{ijt} and the consumer's taste, which is determined by the initial type, θ_{it}, and the interim shocks, η_{kt} and ν_{it}. The marginal utility is

$$u'(x_{ijt}; \theta_{it}, \eta_{kt}, \nu_{it}) = \frac{1}{b} \left(\theta_{it} + \eta_{kt} + \nu_{it} - \log x_{ijt} \right).$$

As a result, the variation of taste shifts a consumer's marginal utility function vertically. I have normalized the utility function so that $u(0; \theta_{it}, \eta_{kt}, \nu_{it}) = 0$ for all θ_{it}, η_{kt}, and ν_{it}. The utility of no consumption is identical for all consumers.

The distribution of initial type θ_{it} depends on household income I_i. In principle, I can add other demographic variables, but the number of parameters in the model will increase exponentially. The variable I_i can be viewed as a proxy for individual i's overall socioeconomic status. Denote the conditional distribution function of θ_{it} by $F_{\theta|I}$. It is normal with mean $\mu_\theta(I_i)$ and variance $\sigma_\theta^2(I_i)$.

$$\theta_{it} | I_i \sim N\left(\mu_\theta(I_i), \sigma_\theta^2(I_i) \right).$$

Since the income distribution varies across regions, the marginal distribution of θ_{it} differs across regions as well. Nonetheless, the income distribution is fixed over time in the model. This implies the distribution of initial taste types θ_{it} is stable over time.

The random shocks, η_{kt} and ν_{it}, are revealed after a rate plan p has been chosen at the beginning of a month. η_{kt} is a *perceived signal quality* index for carrier k at time t. For instance, equipment failure in a network results in a lower realized value. Suppose η_{kt} has a normal distribution,

$$\eta_{kt} \sim N\left(\bar{\eta}_{kt}, \sigma_\eta^2 \right),$$

where the mean is $\bar{\eta}_{kt} = \eta_k^0 + \eta_t^0 + \log(d_t/30)$. A carrier-specific parameter η_k^0 accounts for the heterogeneous perceived qualities among the carriers. A time dummy η_t^0 captures the market-wide factors which influence the willingness to pay at time t. The final term $\log(d_t/30)$ adjusts different number of days, d_t, in a month. Denote the correlation coefficient of η_{kt} across carrier within a period by ρ_η. The random quality shock η_{kt} is independent over time and independent of other variables.[18] Lastly, individual taste shock ν_{it} captures some unexpected personal events, such as being sick. It affects a consumer's willingness to pay for a call after committing to a rate plan. Its distribution is

$$\nu_{it} \sim N\left(0, \sigma_\nu^2\right).$$

It is independent of all other variables. In addition, it is also independent across individuals i and over time t.

Consumers may choose to stay away from any GSM network. Denote the outside option as $k = 0$. Let $K_r^0 \equiv K_r \cup \{0\}$ be the choice set in region r, including the outside option 0. Normalize the fixed effect of the outside option to be $\delta_{0t} = 0$. Hence, the utility of no subscription is ε_{i0t}.

4.2.2 Volume Decision

As in any sequential game, I solve the consumer problem backward. First, consider the volume decision conditional on a given rate plan. Suppose a consumer has subscribed to rate plan p of network k at time t. Since δ_{kt} and ε_{ipt} are fixed values for any given plan p, the volume choices are determined by the first two terms in the utility function (2). The surplus associated with subscribing to this plan choice is

$$\mu_{pt}(\theta_{it}, \eta_{kt}, \nu_{it}, \tau_{it}) \equiv \max_{\mathbf{x}_{it}} \sum_{j \in \mathcal{D}_{it}} u(x_{ijt}; \theta_{it}, \eta_{kt}, \nu_{it}) - \alpha T_{pt}(\mathbf{x}_{it}).$$

The tariff schedule (1) only depends on the total intra-network volume and the total inter-network volume rather than the entire volume vector $\mathbf{x}_{it}$. Moreover, consumers can recognize the carrier of a receiver. As a result, the volume choice x_{ijt} for an individual receiver j is either one of

[18]For instance, higher market share will not cause congestion that lowers the quality.

the following two cases.

$$x_{ijt} = \begin{cases} x^I_{pt}(\theta_{it}, \eta_{kt}, \nu_{it}, \tau_{it}) & \text{if } j\text{'s network is eligible for intra-network discounts;} \\ x^O_{pt}(\theta_{it}, \eta_{kt}, \nu_{it}, \tau_{it}) & \text{if } j\text{'s network is not eligible for intra-network discounts.} \end{cases}$$

The quantity choices solve the following maximization problem.

$$\begin{aligned} (3) \quad & (x^I_{pt}(\theta_{it}, \eta_{kt}, \nu_{it}, \tau_{it}), x^O_{pt}(\theta_{it}, \eta_{kt}, \nu_{it}, \tau_{it})) \equiv \\ & \qquad \arg\max_{x^I, x^O} \ \tau_{it} N^I_{pt} u(x^I; \theta_{it}, \eta_{kt}, \nu_{it}) + \tau_{it} N^O_{pt} u(x^O; \theta_{it}, \eta_{kt}, \nu_{it}) - \alpha T_{pt}(\tau_{it} N^I_{pt} x^I, \tau_{it} N^O_{pt} x^O), \end{aligned}$$

where N^I_{pt} is the total size of networks eligible for intra-network discounts and N^O_{pt} is the size of other networks. The expected network sizes, N^I_{pt} and N^O_{pt}, are fulfilled at equilibrium.

The size of the set of consumer i's receivers, τ_{it}, cannot be separately identified from i's initial taste type θ_{it}. The surplus in the right hand size of (3) can be expressed as

$$\begin{aligned} & \sum_{n=I,O} \frac{\tau_{it} N^n_{pt}}{b} \left\{ [\theta_{it} + \eta_{kt} + \nu_{it} + 1 - \log x^n] x^n \right\} - \alpha T_{pt}(\tau_{it} N^I_{pt} x^I, \tau_{it} N^O_{pt} x^O) \\ = & \sum_{n=I,O} \frac{N^n_{pt}}{b} \left\{ [(\theta_{it} + \log \tau_{it}) + \eta_{kt} + \nu_{it} + 1 - \log(\tau_{it} x^n)] \, (\tau_{it} x^n) \right\} - \alpha T_{pt}(N^I_{pt} \tau_{it} x^I, N^O_{pt} \tau_{it} x^O). \end{aligned}$$

When we compare the surplus and the total intra- and inter-network volumes in a month, there is no distinction between a type-θ_{it} consumer who makes (x^I, x^O) calls to τ_{it} portion of $\mathcal{D}_t$ and a type-$(\theta_{it} + \log \tau_{it})$ consumer who makes $(\tau_{it} x^I, \tau_{it} x^O)$ calls to everybody in $\mathcal{D}_t$. Consequently, let $\tau_{it} = 1$ for all consumers and suppress τ_{it} from the notation.

Because the tariff formula (1) has kinks when the volumes happen to equal the free allowances a^I_{pt} and/or a^O_{pt}, the quantity choice functions have a flat region. The demand function of a type-θ_{it} consumer with shocks (η_{kt}, ν_{it}) is

$$(4) \qquad x^n_{pt}(\theta_{it}, \eta_{kt}, \nu_{it}) = \begin{cases} \exp\left(\theta_{it} + \eta_{kt} + \nu_{it}\right), & \text{if } \eta_{kt} + \nu_{it} < D^n_1(\theta_{it}) \\ \frac{a^n_{pt}}{N^n_{pt}}, & \text{if } D^n_1(\theta_{it}) \le \eta_{kt} + \nu_{it} < D^n_2(\theta_{it}) \\ \exp\left(\theta_{it} + \eta_{kt} + \nu_{it} - \alpha b p^n_{pt}\right), & \text{if } \eta_{kt} + \nu_{it} \ge D^n_2(\theta_{it}) \end{cases}$$

for $n = I, O$, where the boundaries are

$$D_1^n(\theta_{it}) \equiv \log\left(\frac{a_{pt}^n}{N_{pt}^n}\right) - \theta_{it} \qquad \text{and} \qquad D_2^n(\theta_{it}) \equiv \log\left(\frac{a_{pt}^n}{N_{pt}^n}\right) - \theta_{it} + \alpha b p_{pt}^n.$$

The total volume of a type-θ_{it} consumer with shocks η_{kt} and ν_{it} is[19]

$$q_{pt}(\theta_{it}, \eta_{kt}, \nu_{it}) \equiv N_{pt}^I x_{pt}^I(\theta_{it}, \eta_{kt}, \nu_{it}) + N_{pt}^O x_{pt}^O(\theta_{it}, \eta_{kt}, \nu_{it}),$$

and the tariff is

$$\begin{aligned} & T_{pt}(\theta_{it}, \eta_{kt}, \nu_{it}) \\ & = T_{pt}\left(N_{pt}^I x_{pt}^I(\theta_{it}, \eta_{kt}, \nu_{it}),\ N_{pt}^O x_{pt}^O(\theta_{it}, \eta_{kt}, \nu_{it}) \right) \\ \text{(5)} \quad & = MF_{pt} + \sum_{n=I,O} \left\{ \mathbf{1}\{\eta_{kt} + \nu_{it} \geq D_2^n(\theta_{it})\}\, p_{pt}^n \left[N_{pt}^n \exp\left(\theta_{it} + \eta_{kt} + \nu_{it} - \alpha b p_{pt}^n\right) - a_{pt}^n \right] \right\}. \end{aligned}$$

There is a closed-form formula for surplus from calling,

$$\begin{aligned} \text{(6)} \quad \mu_{pt}(\theta_{it}, \eta_{kt}, \nu_{it}) = -\alpha MF_{pt} + \sum_{n=I,O} \Bigg\{ & \mathbf{1}\{\eta_{kt} + \nu_{it} < D_1^n(\theta_{it})\} \left[\frac{N_{pt}^n}{b} e^{\theta_{it} + \eta_{kt} + \nu_{it}} \right] \\ & + \mathbf{1}\{D_1^n(\theta_{it}) \leq \eta_{kt} + \nu_{it} < D_2^n(\theta_{it})\} \frac{a_{pt}^n}{b} \left[\theta_{it} + \eta_{kt} + \nu_{it} + 1 - \log\left(\frac{a_{pt}^n}{N_{pt}^n}\right) \right] \\ & + \mathbf{1}\{\eta_{kt} + \nu_{it} \geq D_2^n(\theta_{it})\} \left[\frac{N_{pt}^n}{b} e^{\theta_{it} + \eta_{kt} + \nu_{it} - \alpha b p_{pt}^n} + \alpha p_{pt}^n a_{pt}^n \right] \Bigg\}. \end{aligned}$$

4.2.3 Discrete Choice of Rate Plans

At the beginning of a month, consumers choose one of the rate plans available in their home region or not to subscribe at all. The choice set includes all plans offered by carriers operating in the region, $\cup_{k \in K_r^0} P_{kt}$.

Because the value of the shocks η_{kt} and ν_{it} are unknown to consumers at the moment of

[19] The physical constraint, $q_{pt}(\theta_{it}, \eta_{kt}, \nu_{it}) \leq d_t \times 24 \times 60 \times 60$ (the total seconds in a month), is abstracted away.

subscription, consumers pick up the rate plan which maximizes their expected utility level.

$$\max_{k\in K_r^0}\max_{p\in P_{kt}}\left\{E_{\eta,\nu}\left[\mu_{pt}(\theta_{it},\eta_{kt},\nu_{it})\right]+\delta_{kt}+\varepsilon_{ipt}\right\}.$$

The expected surplus of rate plan p is obtained from equation (6) by taking expectation over the truncated distributions of (η_{kt},ν_{it}).

$$\begin{aligned}
E_{\eta,\nu}[\mu_{pt}(\theta_{it},\eta_{kt},\nu_{it})] &= -\alpha MF_{pt}\\
&+\sum_{n=I,O}\Bigg\{\Pr(\eta_{kt}+\nu_{it}<D_1^n)E\left[e^{\eta_{kt}+\nu_{it}}|\eta_{kt}+\nu_{it}<D_1^n\right]\frac{N_{pt}^n}{b}e^{\theta_{it}}\\
&\quad+\Pr(D_1^I<\eta_{kt}+\nu_{it}<D_2^n)\frac{a_{pt}^n}{b}\left[E\left[\eta_{kt}+\nu_{it}|D_1^n<\eta_{kt}+\nu_{it}<D_2^n\right]+\theta_{it}+1-\log\left(\frac{a_{pt}^n}{N_{pt}^n}\right)\right]\\
&\quad+\Pr(\eta_{kt}+\nu_{it}>D_2^n)\left[E\left[e^{\eta_{kt}+\nu_{it}}|\eta_{kt}+\nu_{it}>D_2^n\right]\frac{N_{pt}^n}{b}e^{\theta_{it}-\alpha bp_{pt}^n}+\alpha p_{pt}^n a_{pt}^n\right]\Bigg\}.
\end{aligned}$$

Under the normality assumption of η_{kt} and ν_{it}, I can obtain closed-form expressions for the above equation.

The discrete choice follows a nested logit model. The first nest is the choice between *subscription to any plan* and *no subscription*. The second nest after subscription is the choice among all rate plans offered in a consumer's region. Specifically, the distribution function of (ε_{ipt}) is

$$(7)\qquad F_\varepsilon(\varepsilon_{i0t},\varepsilon_{i1t},\varepsilon_{i2t},\dots)=\exp\left(-\exp(-\varepsilon_{i0t})-\left[\sum_{k\in K_r}\sum_{p\in P_{kt}}\exp\left(-\frac{\varepsilon_{ipt}}{\sigma_\varepsilon}\right)\right]^{\sigma_\varepsilon}\right)$$

with $0<\sigma_\varepsilon\leq 1$. The parameter σ_ε measures the degree of the differentiation among the rate plans relative to the on-off decision. When $\sigma_\varepsilon=1$, this model becomes the standard multinomial logit model.[20]

A type-θ_{it} consumer in region r selects rate plan $p\in P_{kt}$ if and only if

$$E_{\eta,\nu}\left[\mu_{pt}(\theta_{it},\eta_{kt},\nu_{it})\right]+\delta_{kt}+\varepsilon_{ipt}\geq E_{\eta,\nu}\left[\mu_{p't}(\theta_{it},\eta_{k't},\nu_{it})\right]+\delta_{k't}+\varepsilon_{ip't},$$

[20]This nested logit specification implies the substitutability between two rate plans is the same after controlling for the expected call surplus $E_{\eta,\nu}[\mu_{pt}(\theta_{it},\eta_{kt},\nu_{it})]$ and the carrier-specific fixed effect δ_{kt}.

for any $p' \in P_{k't}, k' \in K_r^0$. The market share of plan p among consumers with initial taste θ in region r is

$$s_{prt}(\theta) = \frac{\left[\sum_{k' \in K_r} \sum_{p' \in P_{k't}} \exp\left(\frac{E_{\eta,\nu}[\mu_{p't}(\theta,\eta,\nu)]+\delta_{k't}}{\sigma_\varepsilon}\right)\right]^{\sigma_\varepsilon}}{1 + \left[\sum_{k' \in K_r} \sum_{p' \in P_{k't}} \exp\left(\frac{E_{\eta,\nu}[\mu_{p't}(\theta,\eta,\nu)]+\delta_{k't}}{\sigma_\varepsilon}\right)\right]^{\sigma_\varepsilon}} \times \frac{\exp\left(\frac{E_{\eta,\nu}[\mu_{pt}(\theta,\eta,\nu)]+\delta_{kt}}{\sigma_\varepsilon}\right)}{\sum_{k' \in K_r} \sum_{p' \in P_{k't}} \exp\left(\frac{E_{\eta,\nu}[\mu_{p't}(\theta,\eta,\nu)]+\delta_{k't}}{\sigma_\varepsilon}\right)},$$

and the share of the outside option is

$$s_{0rt}(\theta) = \frac{1}{1 + \left[\sum_{k' \in K_r} \sum_{p' \in P_{k't}} \exp\left(\frac{E_{\eta,\nu}[\mu_{p't}(\theta,\eta,\nu)]+\delta_{k't}}{\sigma_\varepsilon}\right)\right]^{\sigma_\varepsilon}}.$$

The national market share is the weighted average over all regions. Let $\Pr(r|I)$ be the proportion of the population in region r conditional on the income I. Then,

$$s_{pt}(I,\theta) = \sum_{r \in R} \Pr(r|I) s_{prt}(\theta) \tag{8}$$

is the national market share for rate plan p at time t conditional on income I and taste type θ.

5 Estimation

Parameters in the behavioral model are obtained by maximum likelihood estimation. Both the carrier-level output data and the household-level expenditure data impose constraints on the parameters through the behavior model. The key variables in the estimation are listed in Table 5. The conditional mean and variance of telecommunication expenditures are obtained from kernel regression. I derive the likelihood function for the total volume VOL_{kt} in this section.

5.1 Simplifications and Notations

The aggregate market share of a plan p at time t is the integration of $s_{pt}(I,\theta)$ over all incomes I and taste types θ. Because there is no closed-form solution for these integrals, I discretize the

Table 5: Variable definition for the structural estimation

Name	Description
Carrier Output Data	
SUB_{kt}	Number of subscribers in network k at time t
VOL_{kt}	Volume of calls originated from network k during period t
Household Survey Data	
$EXP_M(I)$	Mean of telecommunication expenditure condition on income I
$EXP_V(I)$	Variance of telecommunication expenditure condition on I
Other Data	
POP_t	Population at time t

continuous consumer types and use Simpson's Method to approximate the integrals. In order to do so, I transform the (I, θ)-space into the product space of their quantiles, $F_I^{-1}(I) \times F_{\theta|I}^{-1}(\theta)$, where F_I is the distribution function of income, which is log-normal within each region.[21] Consumers are distributed uniformly on the transformed space. I compute the consumption choices for individuals at grid points on the transformed quantile space $[0, 1] \times [0, 1]$.

I only consider the voice service of cellular phones. Although the percentage of the revenue from non-voice service grows steadily, voice service (plus the fixed monthly fee) still accounts for the vast majority of revenue in the industry.[22]

In addition to GSM networks, the set of potential receivers $\mathcal{D}_t$ includes subscribers of landline phones and digital low-powered cordless phones. 3G users are ignored due to lack of reliable monthly data.[23] International calls are also excluded.[24] The expected network sizes, N_{pt}^I and N_{pt}^O, are determined by $\{SUB_{kt}\}$. All calls are assumed to originate from the home region of a consumer. Roaming fees are neglected.

[21]In the numerical approximation, I truncate F_I at its 2.5% and 97.5% percentiles to circumvent the unboundedness of the range of I_i. Similarly, $F_{\theta|I}$ is truncated at the 1% and 99% percentiles.

[22]For example, the proportion of revenue from non-voice services was below 5% for Chunghua Telecom every month between September 2001 and June 2005. See *Operation Data for Most Recent 12 Months* of Chunghua Telecom (`http://www.cht.com.tw/CompanyCat.php?CatID=274`).

[23]There is only one 3G carrier and its market share is small during the research period.

[24]Calls terminated outside Taiwan account for a small portion of the telephone traffic in terms of outgoing minutes although the ratio keeps growing (2000: 1.1%, 2001: 1.7%, 2002: 2.7%, 2003: 4.3%). See Directorate Generate of Telecommunications (2004).

The expenditure survey reports the money amount spent by households on all telecommunication services, not just cellular phone. I assume the expenditure on cellular phone service is a constant fraction λ of the telecommunication budget for all individuals[25]. Consequently, the conditional mean and variance of the expenditure on cellular phone service for a given income level I are $\lambda EXP_M(I)$ and $\lambda^2 EXP_V(I)$, respectively.

Furthermore, the carrier-level output data from the Directorate General of Telecommunications include both residential users and business users while the expenditure survey only covers the former ones. I assume that each carrier has the same proportion of residential users among their subscribers. In addition, the proportion of the volume originated from residential users is the same as the the proportion of residential subscribers. This proportion can be computed for each December between 1999 and 2004 by comparing the number of wireless subscribers in the Directorate General of Telecommunications output data[26] with that in the annual family survey data. For other months, the proportion is obtained by linear interpolation.

The objective of the estimation procedure is to find the model parameters. I group the parameters into three mutually exclusive sets. First, let $\boldsymbol{\delta}$ denote the vector of all carrier-time fixed effects for subscription $\{\delta_{kt} : k \in K, t \in T\}$. Second, I discretize the income space into a finite set $\mathcal{I}$. Let $\Theta \equiv \{\mu_\theta(I), \sigma_\theta^2(I) : I \in \mathcal{I}\}$ denote the parameters for the conditional distribution of initial taste types θ for all income levels $I \in \mathcal{I}$. Third, use Φ to denote the remaining parameters in the model.

5.2 The Moment Condition of the Number of Subscribers

For any given Θ and Φ, I use the numbers of subscribers, $\{SUB_{kt}\}$, to recover the carrier-time fixed effects for subscription $\{\delta_{kt}\}$. Specifically, the system of equations

$$\text{(9)} \qquad \frac{SUB_{kt}}{POP_t} = \sum_{p \in P_{kt}} \iint s_{pt}(I, \theta; \boldsymbol{\delta}_t, \Theta, \Phi)\, dF_{\theta|I}\, dF_I, \qquad \forall k \in K$$

[25] A sufficient condition to obtain a constant share of the expenditure on cellular phone is that (a) all consumers have the same homothetic preferences between cellular phone service and other telecommunications services and (b) prices are linear.

[26] Directorate Generate of Telecommunications (2005) provides the total number of wireless subscribers, including GSM, PHS, and 3G, at the end of each year.

implicitly defines $\boldsymbol{\delta}_t(\Theta, \Phi) = \{\delta_{kt}(\Theta, \Phi) : k \in K\}$ for each t.[27] The following proposition shows that $\boldsymbol{\delta}_t(\Theta, \Phi)$ is well-defined.

Proposition 1. *There is a unique solution $\boldsymbol{\delta}_t$ to the system of equations* (9) *for any given period t.*

Proof. This result is an application of the contracting mapping in Berry et al. (1995). $\square$

In principle, I can stop here and estimate the demand model by the generalized method of moments as in Berry et al. (1995) if I have enough valid instruments for carrier characteristics. Unfortunately, this approach requires a huge number of instruments in my model. Furthermore, identification of the quantity choice and taste heterogeneity only relies on the functional form assumption, not the observed data. Next, I show how to overcome this shortcoming by incorporating data on the expenditure and on the volume.

5.3 The Moment Condition of the Annual Expenditure

Heterogeneities among consumers are identified from the cross-sectional survey data. The average taste strength determines the mean expenditure. Similarly, the dispersion of taste affects the variance of expenditure. Therefore, I use the first and second moments of expenditure to identify $\mu_\theta(I)$ and $\sigma^2_\theta(I)$ for any given income level $I \in \mathcal{I}$.

[27] If switching costs are positive (for instance, a long-term contract with their carrier) for some consumers, the fixed effects $\{\delta_{kt}\}$ might be overestimated. Nonetheless, this bias depends on the correlation of preferences over time. If preferences are similar over time, most consumers would choose the same carrier and switching costs have little effect. In contrast, if preferences are independent over time, many consumers are bound by long-term contracts. The number of consumers who want to choose the outside option would be more than the number of those who actually choose. The utility of the outside option relative the GSM products would be underestimated.

The mean expenditure in the year 2002 conditional on income I is

$$\begin{aligned}
\lambda EXP_M(I) &\equiv \frac{1}{\#\{i : I_i = I\}} \sum_{\{i:I_i=I\}} \sum_{t\in 2002} \sum_{k\in K} \sum_{p\in P_{kt}} \mathbf{1}\{\pi_{it} = p\} T_{pt}(\theta_{it}, \eta_{kt}, \nu_{it}; \Theta, \Phi) \\
&\xrightarrow{p} E_{\varepsilon,\theta,\nu} \left[\sum_{t\in 2002} \sum_{k\in K} \sum_{p\in P_{kt}} \mathbf{1}\{\pi_{it} = p\} T_{pt}(\theta, \eta_{kt}, \nu; \Theta, \Phi) \middle| I \right] \\
&= E_\theta \left[\sum_{t\in 2002} \sum_{k\in K} \sum_{p\in P_{kt}} s_{pt}(I, \theta; \Theta, \Phi) E_\nu [T_{pt}(\theta, \eta_{kt}, \nu; \Theta, \Phi)] \middle| I \right]
\end{aligned}$$

where $\mathbf{1}\{\pi_{it} = p\}$ is an indicator function of consumer i's plan choice π_{it}, which equals 1 if and only if i subscribes to plan p at period t. The limit in the second line holds in probability when the number of individuals with income I goes to infinity. The equality in the last line follows the independence of ε_{ipt}, θ_{it}, and ν_{it}. To ease the notation, I have plugged in the carrier-time fixed effect $\boldsymbol{\delta}_t(\Theta, \Phi)$ and suppressed it in the market share function, $s_{pt}(I, \theta; \Theta, \Phi) = s_{pt}(I, \theta; \boldsymbol{\delta}_t(\Theta, \Phi), \Theta, \Phi)$. Moreover, let

$$AT_{kt}(I, \eta_{kt}; \Theta, \Phi) \equiv E_\theta \left\{ \sum_{p\in P_{kt}} s_{pt}(I, \theta; \Theta, \Phi) E_\nu [T_{pt}(\theta, \eta_{kt}, \nu)] \middle| I \right\}$$

denote the expected tariff received by carrier k from a consumer with income I at time t. As the number of k and t goes to infinity, the Law of Large Numbers implies

$$\frac{1}{12|K|} \sum_{t\in 2002} \sum_{k\in K} AT_{kt}(I, \eta_{kt}; \Theta, \Phi) \xrightarrow{p} \frac{1}{12|K|} \sum_{t\in 2002} \sum_{k\in K} E_\eta [AT_{kt}(I, \eta; \Theta, \Phi)].$$

Therefore, I have the moment condition

$$\lambda EXP_M(I) = \sum_{t\in 2002} \sum_{k\in K} E_\eta [AT_{kt}(I, \eta; \Theta, \Phi)]. \tag{10}$$

The second moment condition depends on the serial correlation of the initial taste type θ_{it}. On the one extreme, suppose $\theta_{it} = \theta_i$ is constant for all periods t in the year 2002. Since the interim taste shock ε_{ipt} is independent over t, I have

$$\Pr(\pi_{it} = p, \pi_{it'} = p'|\theta_i) \;=\; \Pr(\pi_{it} = p|\theta_i)\Pr(\pi_{it'} = p'|\theta_i), \qquad \text{for any } p,\, p' \text{ and } t \neq t'.$$

By definition,

$$\lambda^2 EXP_V(I) \equiv \frac{1}{\#\{i : I_i = I\}} \sum_{\{i:I_i=I\}} \left[\sum_{t\in 2002} \sum_{k\in K^0} \sum_{p\in P_{kt}} \mathbf{1}\{\pi_{it} = p\} T_{pt}(\theta_{it}, \eta_{kt}, \nu_{it}) - \lambda EXP_M(I) \right]^2 .$$

Plug in the moment condition (10) and define $MT_t(I;\Theta,\Phi) = \sum_{k\in K} E_\eta[AT_{kt}(I,\eta;\Theta,\Phi)]$ to be the expected expenditure of a consumer with income I at period t. I obtain

$$\begin{aligned}
&\lambda^2 EXP_V(I) \\
=&\frac{1}{\#\{i : I_i = I\}} \sum_{\{i:I_i=I\}} \left[\sum_{t\in 2002} \left(\sum_{k\in K^0} \sum_{p\in P_{kt}} \mathbf{1}\{\pi_{it} = p\} T_{pt}(\theta_{it}, \eta_{kt}, \nu_{it}) - MT_t(I) \right) \right]^2 \\
=&\frac{1}{\#\{i : I_i = I\}} \sum_{\{i:I_i=I\}} \left[\sum_{t\in 2002} \left(\sum_{k\in K^0} \sum_{p\in P_{kt}} \mathbf{1}\{\pi_{it} = p\} T_{pt}(\theta_{it}, \eta_{kt}, \nu_{it}) - MT_t(I) \right)^2 \right. \\
&\left. + \sum_{t\neq t'} \left(\sum_{k\in K^0} \sum_{p\in P_{kt}} \mathbf{1}\{\pi_{it} = p\} T_{pt} - MT_t(I) \right)\left(\sum_{k'\in K^0} \sum_{p'\in P_{k't'}} \mathbf{1}\{\pi_{it'} = p'\} T_{p't'} - MT_{t'}(I) \right) \right].
\end{aligned}$$

As the number of consumers with income I goes to infinity,

$$
\begin{aligned}
&\lambda^2 EXP_V(I)\\
&\xrightarrow{p} E_{\varepsilon,\theta,\nu}\Bigg[\sum_{t\in 2002}\Big(\sum_{k\in K^0}\sum_{p\in P_{kt}}\mathbf{1}\{\pi_{it}=p\}T_{pt}(\theta_{it},\eta_{kt},\nu_{it})-MT_t(I)\Big)^2\\
&\quad+\sum_{t\neq t'}\Big(\sum_{k\in K^0}\sum_{p\in P_{kt}}\mathbf{1}\{\pi_{it}=p\}T_{pt}-MT_t(I)\Big)\Big(\sum_{k'\in K^0}\sum_{p'\in P_{k't'}}\mathbf{1}\{\pi_{it'}=p'\}T_{p't'}-MT_{t'}(I)\Big)\Bigg|I\Bigg]\\
&=E_\theta\Bigg[\sum_{t\in 2002}\sum_{k\in K^0}\sum_{p\in P_{kt}} s_{pt}(\theta,I)E_\nu\left[(T_{pt}(\theta,\eta_{kt},\nu)-MT_t(I))^2\right]\\
&\quad+\sum_{t\neq t'}\Big(\sum_{k\in K^0}\sum_{p\in P_{kt}}s_{pt}(\theta,I)E_\nu[T_{pt}-MT_t(I)]\Big)\Big(\sum_{k'\in K^0}\sum_{p'\in P_{k't'}}s_{p't'}(\theta,I)E_\nu[T_{p't'}-MT_{t'}(I)]\Big)\Bigg|I\Bigg]
\end{aligned}
$$

Apply the Law of Large Numbers on $\{\eta_{kt}\}$. I obtain the moment condition.

$$
\begin{aligned}
(11)\quad \lambda^2 EXP_V(I) = E_\theta\Bigg[&\sum_{t\in 2002}\sum_{k\in K^0}\sum_{p\in P_{kt}} s_{pt}(\theta,I)E_{\eta,\nu}\left[(T_{pt}(\theta,\eta,\nu)-MT_t(I))^2\right]\\
&+\sum_{t\neq t'}\Big(\sum_{k\in K^0}\sum_{p\in P_{kt}}s_{pt}(\theta,I)E_\nu[T_{pt}-MT_t(I)]\Big)\Big(\sum_{k'\in K^0}\sum_{p'\in P_{k't'}}s_{p't'}(\theta,I)E_{\eta,\nu}[T_{p't'}-MT_{t'}(I)]\Big)\Bigg|I\Bigg].
\end{aligned}
$$

On the other extreme, suppose the initial taste type θ_{it} is independent over time t. The second term on the right hand side of the equation (11) would disappear in this case. The moment condition becomes

$$
\lambda^2 EXP_V(I) = E_\theta\Bigg[\sum_{t\in 2002}\sum_{k\in K^0}\sum_{p\in P_{kt}} s_{pt}(\theta,I)E_{\eta,\nu}\left[(T_{pt}(\theta,\eta,\nu)-MT_t(I))^2\right]\Bigg|I\Bigg].
$$

In general, the serial correlation of $\{\theta_{it}\}$ is between these two extreme cases. I can express the second-moment condition as

$$(12)\quad \lambda^2 EXP_V(I) =$$

$$E_\theta\Bigg[\sum_{t\in 2002}\sum_{k\in K^0}\sum_{p\in P_{kt}} s_{pt}(\theta,I;\Theta,\Phi)E_{\eta,\nu}\left[(T_{pt}(\theta,\eta,\nu;\Theta,\Phi)-MT_t(I;\Theta,\Phi))^2\right]$$
$$+\rho_\theta\sum_{t\neq t'}\Bigg(\sum_{k\in K^0}\sum_{p\in P_{kt}} s_{pt}(\theta,I;\Theta,\Phi)E_\nu[T_{pt}(\theta,\eta,\nu;\Theta,\Phi)-MT_t(I;\Theta,\Phi)]\Bigg)\times$$
$$\Bigg(\sum_{k'\in K^0}\sum_{p'\in P_{k't'}} s_{p't'}(\theta,I)E_{\eta,\nu}[T_{p't'}(\theta,\eta,\nu;\Theta,\Phi)-MT_{t'}(I;\Theta,\Phi)]\Bigg)\Bigg|I\Bigg]$$

for some parameter ρ_θ to be estimated. ρ_θ is increasing in the serial correlation of consumer's initial taste types $\{\theta_{it}\}$.

The $2|\mathcal{I}|$ moment conditions described in (10) and (12) exactly identify the conditional distribution of initial taste type θ at all income levels $I\in\mathcal{I}$ for any given parameter Φ. Thus, I can express the mean and variance of the conditional distributions as $\Theta(\Phi)$.

5.4 The Moment Condition of Total Volume

Next, use the information contained in the total volume of calls in each network.

$$\frac{VOL_{kt}}{POP_t} = \sum_{p\in P_{kt}}\iiint s_{pt}(I,\theta;\boldsymbol{\delta}_t(\Theta(\Phi),\Phi),\Theta(\Phi),\Phi)q_{pt}(\theta,\eta_{kt},\nu;\Theta(\Phi),\Phi)\,dF_\nu\,dF_{\theta|I}\,dF_I$$
$$\xrightarrow{p}\sum_{p\in P_{kt}}\iint s_{pt}(I,\theta;\boldsymbol{\delta}_t(\Theta(\Phi),\Phi),\Theta(\Phi),\Phi)E_\nu\left[q_{pt}(\theta,\eta_{kt},\nu;\Theta(\Phi),\Phi)\right]\,dF_{\theta|I}\,dF_I$$

The above limit holds in probability when the number of consumers goes to infinity. Under this condition (and suppressing $\boldsymbol{\delta}_t$ and Θ), I have

$$(13)\qquad \frac{VOL_{kt}}{POP_t} = \sum_{p\in P_{kt}}\iint s_{pt}(I,\theta;\Phi)E_\nu[q_{pt}(\theta,\eta_{kt},\nu;\Phi)]\,dF_{\theta|I}\,dF_I.$$

The above equation implicitly defines a function $\eta_{kt}\equiv G_{kt}(VOL_{kt}/POP_t;\Phi)$. The following proposition shows that G is well-defined for any $VOL_{kt}>0$.

Proposition 2. *For any given parameters Φ, there is a unique solution of η_{kt} to equation* (13) *whenever $VOL_{kt} > 0$.*

Proof. By definition, the expected total volume over the individual shock ν_{it} is $E_\nu[q_{pt}(\theta, \eta_{kt}, \nu; \Phi)] = N^I_{pt} E_\nu[x^I_{pt}(\theta, \eta_{kt}, \nu; \Phi)] + N^O_{pt} E_\nu[x^O_{pt}(\theta, \eta_{kt}, \nu; \Phi)]$. Obviously, this is a strictly increasing function in η_{kt}. Moreover, $s_{pt}(I_{it}, \theta_{it}; \Phi) > 0$ does not depend on η_{kt}. As a result, the right-hand side of (13) is a monotonic function of η_{kt}. Furthermore, $E_\nu[x^n_{pt}(\theta, \eta_{kt}, \nu)] \to +\infty$ as $\eta_{kt} \to +\infty$ and $E_\nu[x^n_{pt}(\theta, \eta_{kt}, \nu)] \to 0$ as $\eta_{kt} \to -\infty$. Therefore, for any $VOL_{kt} > 0$, there is a unique solution of η_{kt} to equation (13). □

5.5 Likelihood Function

The cumulative distribution function of VOL_{kt}/POP_t is

$$\Pr\left(\frac{VOL_{kt}}{POP_t} \leq x; \Phi\right) = \Pr(\eta_{kt} < G_{kt}(x; \Phi)).$$

Let $\boldsymbol{\eta}_t$ denote the random vector $(\eta_{kt} : k \in K)$. Express its mean by $\bar{\boldsymbol{\eta}}_t \equiv (\bar{\eta}_{kt} : k \in K)$ and its covariance by Σ_η. In addition, let $\boldsymbol{G}_t(\boldsymbol{x}; \Phi) \equiv (G_{kt}(x_k; \Phi) : k \in K)$. Recall that $\boldsymbol{\eta}_t \sim N(\bar{\boldsymbol{\eta}}_t, \Sigma_\eta)$. Consequently, the density function of $(VOL_{kt}/POP_t : k \in K)$ is

$$f_V(\boldsymbol{x}; \Phi) \equiv (2\pi)^{-\frac{|K|}{2}} |\Sigma_\eta|^{-\frac{1}{2}} \exp\left(-\frac{1}{2}\left[\boldsymbol{G}_t(\boldsymbol{x}; \Phi) - \bar{\boldsymbol{\eta}}_t\right]' \Sigma_\eta^{-1} \left[\boldsymbol{G}_t(\boldsymbol{x}; \Phi) - \bar{\boldsymbol{\eta}}_t\right]\right) |\nabla G_t(\boldsymbol{x}; \Phi)|.$$

Take the logarithm of the density function. I obtain

$$\begin{aligned} \log f_V(\boldsymbol{x}; \Phi) = &-\frac{1}{2}\left[\boldsymbol{G}_t(\boldsymbol{x}; \Phi) - \bar{\boldsymbol{\eta}}_t\right]' \Sigma_\eta^{-1} \left[\boldsymbol{G}_t(\boldsymbol{x}; \Phi) - \bar{\boldsymbol{\eta}}_t\right] \\ &- \frac{1}{2}\log|\Sigma_\eta| + \log|\nabla \boldsymbol{G}_{kt}(\boldsymbol{x}; \Phi)| - \frac{|K|}{2}\log(2\pi). \end{aligned}$$

Since the quality shock η_{kt} is independent over t, the log-likelihood function is

$$L(\Phi) = \sum_t \log f_V\left(\left(\frac{VOL_{kt}}{POP_t} : k \in K\right); \Phi\right).$$

The parameter Φ is estimated by

$$\hat{\Phi} = \arg\max_{\Phi} L(\Phi).$$

The other parameters are subsequently obtained through $\hat{\Theta} = \Theta(\hat{\Phi})$ and $\hat{\boldsymbol{\delta}} = \boldsymbol{\delta}(\Theta(\hat{\Phi}), \hat{\Phi})$.

5.6 Identification

I now provide a discussion of how variations in the data identify the parameters in the demand model. The marginal disutility of expenditure α is identified from the sensitivity of demand with respect to change in flat monthly fees. Marginal price varies within a rate plan and across rate plans. For any given α, these price variations identify the scale of the utility from calling, b. The parameters for the distribution of signal quality index η_{kt} are identified from the average volume per customer after controlling for the price difference. The fixed effect for subscription δ_{kt} is identified from the number of subscribers in network k for a given calling surplus. Identification of the substitution parameter in the nested logit model, σ_{ε}, comes from the change in the total subscription rate relative to the change in the market share of individual carriers with respect to price variation. The percentage of the expenditure on cellular service, λ, is identified from the difference between the average tariff imputed from the output data and the average telecommunication expenditure in the household survey. Finally, the parameter for the serial correlation of initial taste types, ρ_{θ}, is identified from the variation of the tariffs imputed from the monthly Directorate General of Telecommunications statistics relative to the observed variance of annual expenditure in the survey.

Since there are no data on an individual consumer's choice in a single period, the variance of individual interim shock σ_{ν}^2 can only be identified through functional form assumptions.[28]

6 Empirical Results

6.1 Estimated Parameters

The main estimation results are reported on Table 6. Three different specifications are presented here. The mean of signal quality index η_t^0 is restricted to a constant over time in column I. It is

[28]There is only a second order effect of these individual shocks in the aggregate level.

Table 6: Parameter estimates of the structural model

Parameter	Description	I	II	III
1000α	Marginal disutility of payment	7.2293 (3.0019)	7.1892 (1.9242)	7.1595 (1.6333)
$0.001b$	Scale parameter of utility	0.5435 (0.2007)	0.5440 (0.1404)	0.4960 (0.1035)
λ	Share of cellular expenditure	0.5957 (0.0107)	0.5853 (0.0103)	0.5452 (0.0071)
σ_ε	Substitution parameter	0.6657 (0.3281)	0.6393 (0.1691)	0.5957 (0.1722)
ρ_θ	Correlation of θ over time	0.9614 (0.1653)	0.9482 (0.1363)	0.9499 (0.1257)
η^0_{TCC}	Quality index of TCC	-0.1821 (0.0584)	-0.1757 (0.0568)	-0.2370 (0.0797)
η^0_{FET}	Quality index of FET	-0.1895 (0.0937)	-0.1664 (0.0626)	-0.2310 (0.0811)
η^0_{KGT}	Quality index of KGT	-0.2729 (0.0472)	-0.2614 (0.0549)	-0.2897 (0.0432)
η^0_{TAT}	Quality index of TAT	-0.4039 (0.0589)	-0.4212 (0.0745)	-0.5266 (0.0512)
η^0_{MBT}	Quality index of MBT	-0.3495 (0.0480)	-0.4028 (0.0693)	-0.4098 (0.0466)
η^0_{2000}	Quality index of 2000		0.2987 (0.0634)	
η^0_{2001}	Quality index of 2001		0.0271 (0.0452)	
η^0_{2003}	Quality index of 2003		-0.2025 (0.0445)	
η^0_{2004}	Quality index of 2004		0.0451 (0.0451)	
η^0_{2005}	Quality index of 2005		0.3477 (0.1068)	
$0.001\gamma_1$	Time trend of quality index			-0.4593 (0.8955)
$0.001\gamma_2$	Squared term of time trend			0.5993 (0.0490)
σ^2_η	Variance of quality shock	0.1567 (0.0193)	0.1179 (0.0113)	0.1049 (0.0100)
ρ_η	Correlation of quality shock	0.2053 (0.0879)	-0.0696 (0.0316)	-0.1576 (0.0148)
Log-Likelihood		-1789.4	-1730.0	-1714.5

Notes: Standard errors are in parentheses. There are 372 observations. Estimates for the variance of individual demand shocks are close to zero ($\hat{\sigma}_\nu = 2 \times 10^{-4}$) and insignificant. The number of grid points on the quantile space is 11×11.

assumed to be a yearly dummy in column II.

$$\eta_t^0 = \eta_{year}^0 \, \mathbf{1}[t \in year].$$

I normalize η_{2002} to be zero. In column III, I assume the mean value is a quadratic function over time,

$$\eta_t^0 = \gamma_1(t-30) + \gamma_2(t-30)^2,$$

where I normalize the value for the 30th period (October 2002) to be zero. There is no significant difference among these three specifications on the parameter estimates except for $\hat{\eta}_{TAT}^0$.

The following discussions focus on the empirical result under specification III. All parameters except γ_1 are significantly different from zero. The marginal disutility of payment, α, is positive as expected. The utility from making cellular calls is positive since $\hat{b} > 0$. The estimated share of expenditure on cellular phone service among telecommunication budget is 54.5%. The substitution parameter in the nested logit model is $\hat{\sigma}_\varepsilon = 0.60$, which is significantly different from one. The substitution among rate plans significantly differs from the on-off substitution. The estimate of ρ_θ is close to one, implying that the initial taste type θ_{it} is highly correlated over time for a given consumer.

Conditional on subscription, signal quality indices significantly differ across carriers and over time. Since the marginal utility of consuming x_{ijt} seconds has a monetary value $(\theta_{it} + \eta_{kt} + \nu_{it} - \log x_{ijt})/b/\alpha$, the quality difference can be compared by the marginal utility at any given quantity. Table 7 reports the difference between any pair of carriers. Chunghua Telecom provides the highest value. It is followed by Far Eastone and Taiwan Cellular. KG Telecommunication is slightly lower. The two regional networks, Trans Asia and Mo Bi Tai, appear to have the lowest quality. In addition, the mean signal quality index decreases from 0.1457 Taiwan dollars per second in May 2000 to zero in October 2002 and increases afterwards to 0.1687 Taiwan dollars in June 2005. These quality differences are considerable when comparing to the marginal prices, which range from 0 to 0.2227 Taiwan dollars per second.

Interim shocks are important in the volume decision. The estimated variance of the quality

Table 7: Signal quality difference between carriers

	CHT	TCC	EFT	KGT	TAT
TCC	-0.0667				
	(0.0226)				
FET	-0.0651	0.0017			
	(0.0249)	(0.0334)			
KGT	-0.0816	-0.0148	-0.0165		
	(0.0102)	(0.0164)	(0.0249)		
TAT	-0.1483	-0.0815	-0.0832	-0.0667	
	(0.0118)	(0.0153)	(0.0222)	(0.0064)	
MBT	-0.1154	-0.0487	-0.0504	-0.0338	0.0329
	(0.0106)	(0.0186)	(0.0222)	(0.0076)	(0.0062)

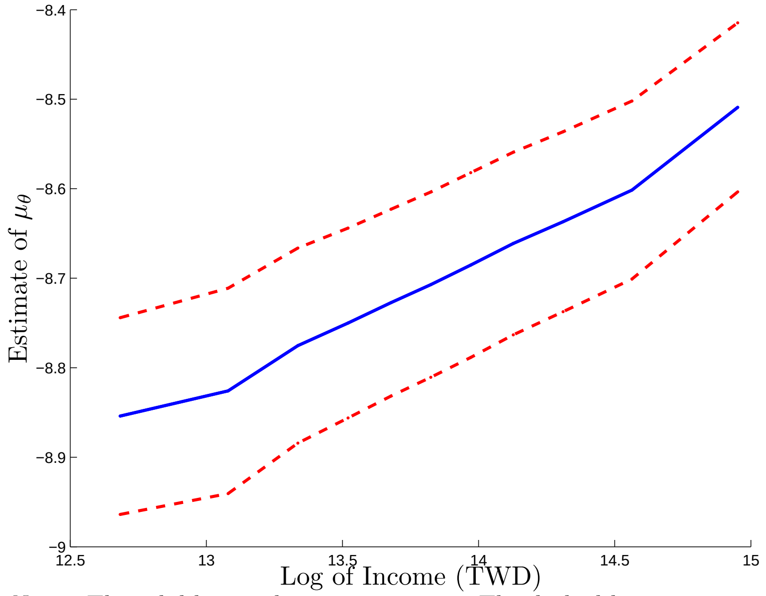
Notes: The number in entry (i, j) is the marginal utility of subscribing to carrier i relative to carrier j. Standard errors are in parentheses. Unit: TWD/second.

shock, $\hat{\sigma}_\eta^2 = 0.1049$, is significantly positive. A positive shock of η_{kt} with one standard deviation would increase the marginal utility by 0.0295 Taiwan dollars per second. Equivalently, the volume would raise 11% under linear pricing.

The conditional distribution of initial taste types θ is obtained from $\hat{\Theta} = \Theta(\hat{\Phi})$. The estimated conditional means, $\{\hat{\mu}_\theta(I)\}$, are shown in Figure 1.[29] As expected, the conditional mean is an increasing function of income I. A consumer in a wealthy household tends to use more cellular phone service, ceteris paribus. Specifically, an individual in a 90% income percentile household on average values a second of cellular service 0.0711 Taiwan dollars more than a person in a 10% income percentile household. This difference would imply 25% more volume under linear pricing. Furthermore, after controlling for the household income, consumers still differ in their calling taste. Figure 2 presents the estimated standard deviations conditional on income. The estimated standard deviations $\{\hat{\sigma}_\theta(I)\}$ are significantly positive, but there is no clear relationship between $\hat{\sigma}_\theta(I)$ and income I.

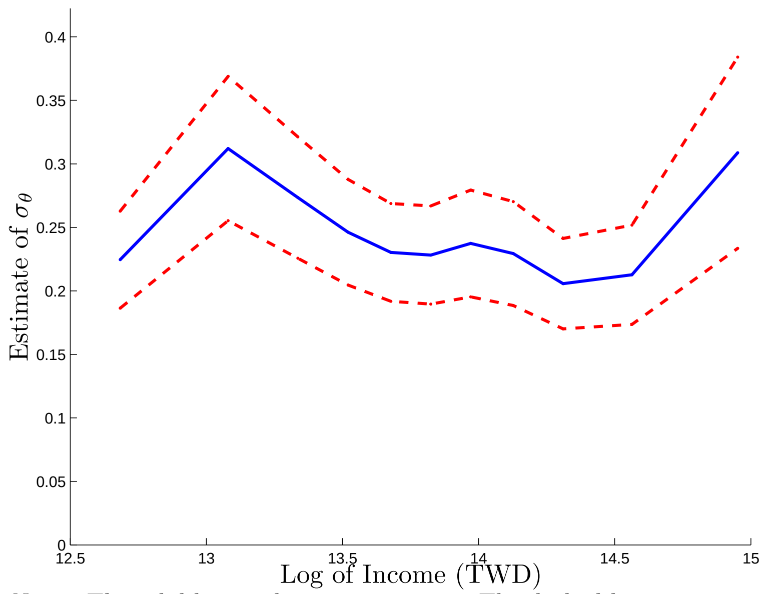
There is substantial variation of initial taste type θ_{it} among consumers. The variance of θ_{it} among all consumers is 0.0676, which implies the standard deviation of marginal utility in this

[29] The magnitude of the initial taste type θ_{it} can be interpreted in terms of marginal utility. Suppose the interim shocks, η_{kt} and ν_{it}, are both zero. The mean of $\theta_i t$ is -8.7072 at the median income, which means the marginal utility is 0.0609 Taiwan dollars per second for a consumer who makes 50 minutes of calls a month.



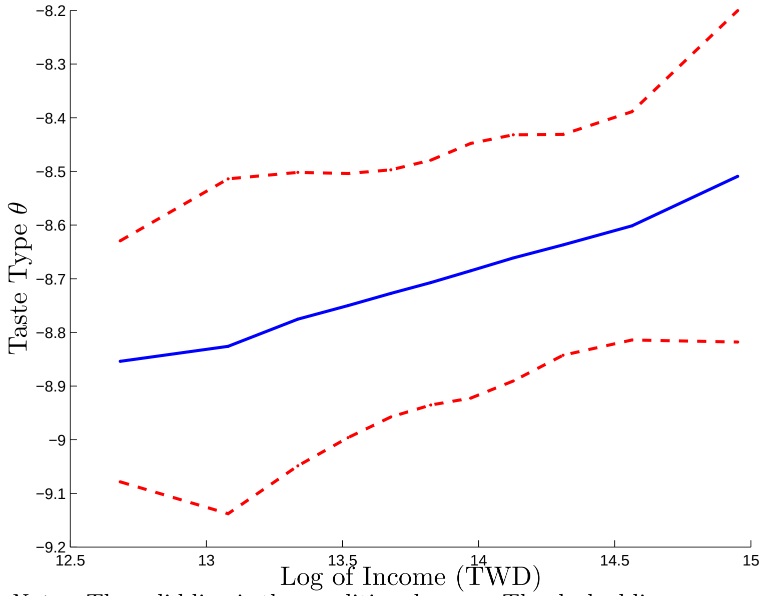
Notes: The solid line is the point estimate. The dashed lines represent the 95% confidence interval.

Figure 1: Mean of initial taste type θ conditional on income



Notes: The solid line is the point estimate. The dashed lines represent the 95% confidence interval.

Figure 2: Standard deviation of initial taste type θ conditional on income



Notes: The solid line is the conditional mean. The dashed lines are one standard deviation away from the mean.

Figure 3: Distribution of initial taste type θ conditional on income

market is 0.0732 Taiwan dollars per second for any given quantity. By using the point estimates of $\mu_\theta(I)$ and $\sigma_\theta(I)$, the conditional distribution of θ is shown in Figure 3. The variation of θ_{it} conditional on income is large when comparing to the difference of θ_{it} explained by income. Income variation only accounts for 9.79% of the taste variation.

Finally, the fixed effects for subscription can be obtained from $\hat{\boldsymbol{\delta}} = \boldsymbol{\delta}(\Theta(\hat{\Phi}), \hat{\Phi})$. In Figure 4, the estimated fixed effects are expressed in the monetary value $\hat{\delta}_{kt}/\hat{\alpha}$. Relative to the outside option, the median value of subscribing to a GSM network is -1269 Taiwan dollars after excluding the surplus from making phone calls, $\mu_{pt}(\theta_{it}, \eta_{kt}, \nu_{it})$. Therefore, for a consumer who does not want to make any outgoing phone call, the hassle cost of connecting to a GSM network (e.g. the cost of buying a handset) outweighs its value (e.g. receiving incoming phone calls) if the net value of the outside choice is normalized to zero. The value of fixed effects decreases after 2003. This is consistent with the introduction of alternative wireless services, PHS and 3G. Note that while Chunghua Telecom has the highest signal quality index η^0_{CHT} and Trans Asia has the lowest index η^0_{TAT}, the order is reversed for the fixed effects δ_{CHTt} and δ_{TATt}. The median of the differences between these two carriers is 590 Taiwan dollars.

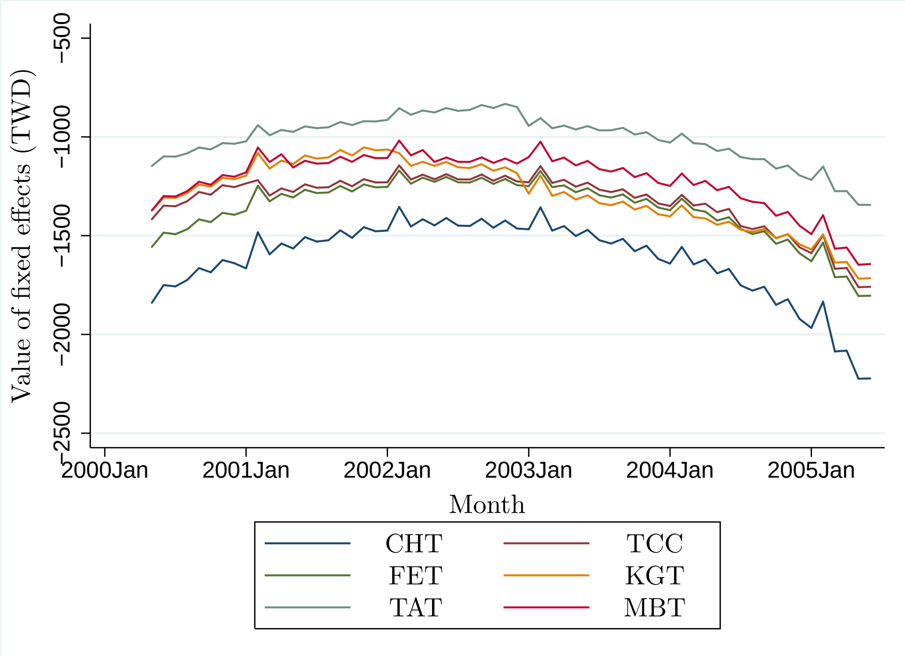


Figure 4: Fixed effects for subscription

6.2 Demand Elasticities

I use the estimated model to compute demand elasticities. The median industry-wide demand elasticity for a proportional change in price schemes is -1.093 for the number of subscribers and -1.2073 for the total volume. Because increase in price would reduce the number of subscribers and the usage of the remaining customers, the latter elasticity is greater than the former (in absolute value).[30] The demand elasticities at the carrier level are presented in Table 8. The demand is elastic for all carriers. While all other carriers have similar own-price elasticities, Trans Asia has a substantial lower elasticity. This suggests the service of Trans Asia is more differentiated from other five carriers. Besides, price change of a large network has a stronger impact on rival networks than that of a small network.

In addition to the price schemes, the demand for cellular phone service also depends on the expected network sizes. Table 9 shows that demand increases in own network size. It is less

[30]Parker and Röller (1997) estimate the elasticity at −2.456 in a linear regression model for U.S. cellular market between 1984 and 1988. Hausman (1997) estimates the elasticity at -0.506 for top 30 U.S. cellular markets in 1989 – 1993.

Table 8: Median own- and cross-price elasticities

	CHT	TCC	FET	KGT	TAT	MBT
Number of Subscribers						
CHT	-5.9657	1.4624	1.0292	0.8221	0.1353	0.1330
TCC	2.2620	-5.1657	1.0130	0.8189	0.1629	0.1337
FET	2.2843	1.4125	-5.7969	0.8203	0.1760	0.1334
KGT	2.0688	1.4264	0.9950	-5.4001	0.1668	0.1355
TAT	1.0509	0.9591	0.7073	0.5664	-3.8232	0.0000
MBT	2.0160	1.3238	0.9378	0.7810	0.0000	-5.3809
Total Volume						
CHT	-6.1620	1.4338	1.0168	0.8487	0.1162	0.1270
TCC	2.5958	-5.6089	1.0473	0.8339	0.1513	0.1366
FET	2.5760	1.4585	-6.3781	0.8370	0.1642	0.1356
KGT	2.6923	1.4535	1.0228	-6.3074	0.1614	0.1378
TAT	1.2793	1.0473	0.7715	0.6264	-4.4209	0.0000
MBT	2.5036	1.3742	0.9827	0.8097	0.0000	-5.7143

Note: Cell entries (i, j), where i indexes row and j column, give the percentage change in network i with respect to a 1% proportional price change of network j. Each entry represents the median of the elasticities from 62 periods.

Table 9: Median demand elasticities with respect to expected network sizes

	CHT	TCC	FET	KGT	TAT	MBT
Number of Subscribers						
CHT	1.1936	0.4689	0.3718	0.2939	0.1282	0.0647
TCC	0.1733	0.6383	0.1844	0.1831	0.0919	0.0360
FET	0.1831	0.2304	0.4903	0.1571	0.0639	0.0321
KGT	0.1969	0.2478	0.2310	0.4288	0.0525	0.0386
TAT	-0.0619	-0.0034	-0.0038	0.0016	0.0586	0.0052
MBT	0.2736	0.3170	0.2401	0.2122	0.0801	0.0619
Total Volume						
CHT	1.3426	0.5825	0.4468	0.3594	0.1541	0.0774
TCC	0.2544	0.7615	0.2521	0.2487	0.1236	0.0481
FET	0.2678	0.3168	0.5875	0.2127	0.0799	0.0437
KGT	0.2899	0.3654	0.2975	0.5469	0.0744	0.0496
TAT	0.0534	0.1261	0.0732	0.0630	0.0782	0.0165
MBT	0.3968	0.4523	0.3423	0.2937	0.1090	0.0759

Note: Cell entries (i, j), where i indexes row and j column, give the percentage change in network i with respect to a 1% change in the size of network j. Each entry represents the median of the elasticities from 62 periods.

sensitive to network sizes than to prices. The cross effects are ambiguous. When the size of one carrier increases, there are two effects. On the one hand, the pool of potential receivers grows, this increases the overall demand for phone service for any given consumer. On the other hand, this carrier becomes relatively more attractive than others because of intra-network discounts. This reduces the demand for its rivals. As the table demonstrates, the cross effects are positive for most carriers, but they are negative on subscription for Trans Asia when the size of Chunghua Telecom, Taiwan Cellular, or Far Eastone increases.

7 Counterfactual Simulations

7.1 Evaluation of Intra-Network Discounts

For a given percentage of intra-network discounts, the average price of a rate plan in a large network reduces more than that in a small network because there is a higher probability of making an intra-network call. Consumers are more likely to subscribe to a rate plan offered by a large carrier. Based on the behavior model, I perform a counterfactual simulation to quantify the effect of intra-network discounts on the market demand.

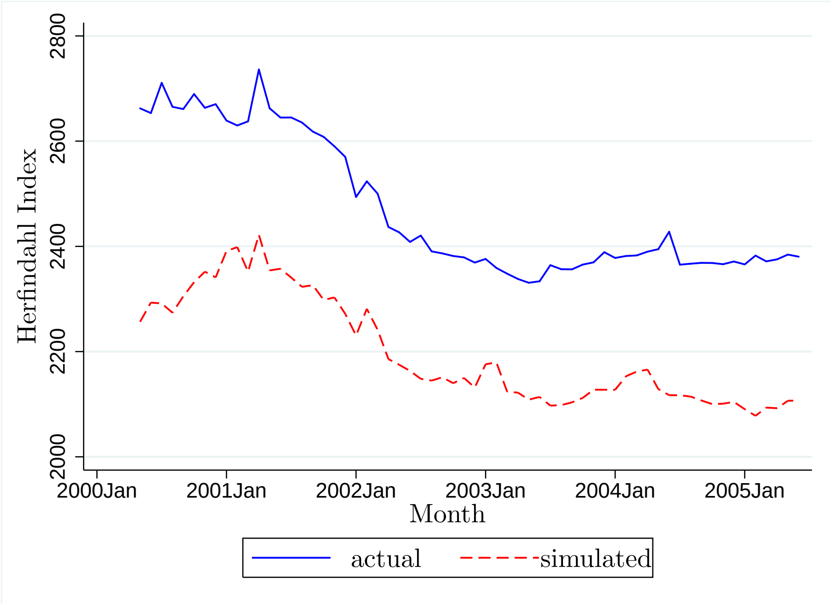
The first column in Table 10 is the actual outcome in December 2003. Suppose intra-network discounts are not allowed and all calls (exceeding the free allowance threshold) are priced at the observed inter-network rate. The simulated result is on the second column of the table. While the average price goes up, the average consumption goes down. Consumer surplus reduces modestly by 5.4%. Nevertheless, there are large impacts on the relative market shares. The variation of network sizes among the carriers becomes much less when the intra-network discounts are eliminated. For instance, the largest carrier, CHT, loses 43% of its subscribers, but the smallest one, MBT, gains 39%. Meanwhile, the revenue of CHT decreases by 40%, but that of MBT increases by 42%. The market shares of the four national carriers become very close.

Figure 5 shows the HHI measured in total volume for each period. When intra-network discounts are eliminated, the median of the change in the indices is 264 points. The quartiles are 242 and 298 points. Although there is no clear guidance to interpret the change in HHI due to price discrimination, the Department of Justice (1994)'s horizontal merger guidelines says "Where the

Table 10: Counterfactual simulation on no intra-network discount

	Actual	Simulated
Average Usage (minutes)	43.17	41.10
Average Expenditure (TWD)	306.79	296.59
Average Expected Consumer Surplus (TWD)	203.60	192.51
Number of Subscribers (millions)		
CHT	3.8151	2.1777
TCC	2.6816	2.4850
FET	2.0449	2.1150
KGT	1.6937	2.3426
TAT	1.0154	1.3799
MBT	0.3276	0.4557
Total	11.5783	10.9559
Aggregate Volume (million minutes)		
CHT	338.45	186.40
TCC	217.29	199.30
FET	162.45	171.93
KGT	191.93	271.80
TAT	45.12	69.88
MBT	20.51	29.83
Total	975.75	929.13
Revenue (billion TWD)		
CHT	2.5139	1.5163
TCC	1.5639	1.5148
FET	1.2456	1.3662
KGT	1.0417	1.4489
TAT	0.3916	0.6058
MBT	0.1780	0.2523
Total	6.9348	6.7043

Note: Calculated for December of 2003.



Note: Intra-network discounts are eliminated in the simulation.

Figure 5: Simulated market concentration rates without discounts

post-merger HHI exceeds 1800, it will be presumed that mergers producing an increase in the HHI of more than 100 points are likely to create or enhance market power or facilitate its exercise." The change in HHI is large by this standard. The concentration rate change due to intra-network discounts is equivalent to a horizontal merger between two firms with 11.5% market shares.

The simulated result shows that intra-network discounts in the Taiwanese cellular market change the market structure considerably. The discounts shift subscribers from smaller carriers toward larger ones and significantly raise the market concentration rate. Such discounts are effective tools to alter market competition. Antitrust agency needs to concern about the impact of termination-based price discrimination. However, long-term effects are beyond the scope of this paper.

7.2 Evaluation of Carrier Recognizability

I now consider the case in which consumers cannot recognize the carrier of a receiver. For example, after number portability is introduced into the market, consumers can switch to a different cellular carrier without changing the phone number. The prefix of a phone number is not a valid indicator for the carrier. Alternatively, if phone numbers are not assigned to carriers with distinguishable prefixes, such as in the U.S. cellular service market, consumers cannot know the carrier of a receiver from the phone number.

Suppose consumers only know the market shares of all networks, but they have no information about the carrier of each individual receiver. It is impossible to choose calling volumes according to the termination. Without loss of generality, assume $a^I_{pt}/N^I_{pt} \geq a^O_{pt}/N^O_{pt}$. Let $N_t = N^I_{pt} + N^O_{pt}$ be the total number of receivers. The demand function of a type θ_{it} consumer with shocks (η_{kt}, ν_{it}) becomes

$$x_{pt}(\theta_{it}, \eta_{kt}, \nu_{it}) = \begin{cases} \exp\left(\theta_{it} + \eta_{kt} + \nu_{it} - \alpha b \bar{p}_{pt}\right), & \text{if } \eta_{kt} + \nu_{it} \geq B_4(\theta_{it}) \\ \frac{a^I_{pt}}{N^I_{pt}}, & \text{if } B_3(\theta_{it}) \leq \eta_{kt} + \nu_{it} < B_4(\theta_{it}) \\ \exp\left(\theta_{it} + \eta_{kt} + \nu_{it} - \alpha b \bar{p}^O_{pt}\right), & \text{if } B_2(\theta_{it}) \leq \eta_{kt} + \nu_{it} < B_3(\theta_{it}) \\ \frac{a^O_{pt}}{N^O_{pt}}, & \text{if } B_1(\theta_{it}) \leq \eta_{kt} + \nu_{it} < B_2(\theta_{it}) \\ \exp\left(\theta_{it} + \eta_{kt} + \nu_{it}\right), & \text{if } \eta_{kt} + \nu_{it} < B_1(\theta_{it}) \end{cases},$$

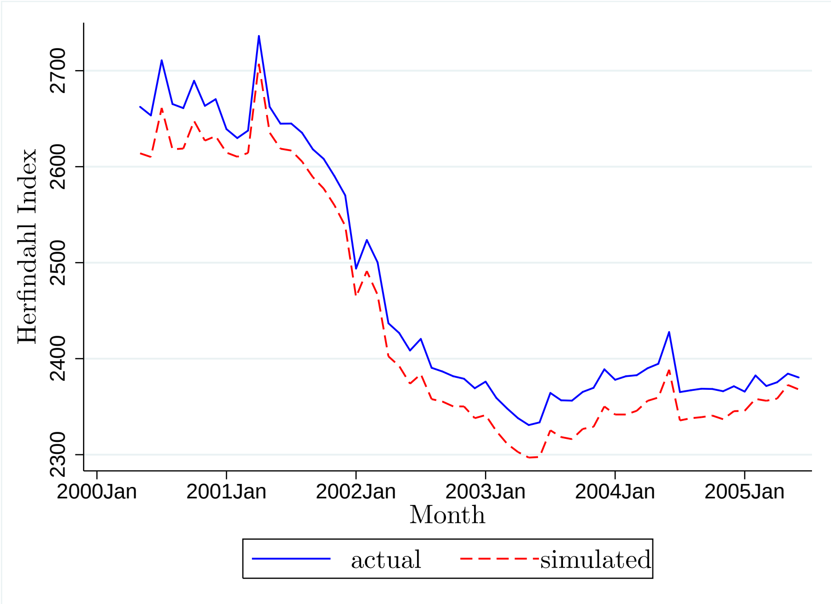
where $\bar{p}_{pt} = (N^I_{pt} p^I_{pt} + N^O_{pt} p^O_{pt})/N_t$, $\bar{p}^O_{pt} = N^O_{pt} p^O_{pt}/N_t$ and the boundaries are

$$B_1(\theta_{it}) \equiv \log\left(\frac{a^O_{pt}}{N^O_{pt}}\right) - \theta_{it}\,, \qquad B_2(\theta_{it}) \equiv \log\left(\frac{a^O_{pt}}{N^O_{pt}}\right) - \theta_{it} + \alpha b \bar{p}^O_{pt}\,,$$

$$B_3(\theta_{it}) \equiv \log\left(\frac{a^I_{pt}}{N^I_{pt}}\right) - \theta_{it} + \alpha b \bar{p}^O_{pt}\,, \text{ and} \qquad B_4(\theta_{it}) \equiv \log\left(\frac{a^I_{pt}}{N^I_{pt}}\right) - \theta_{it} + \alpha b \bar{p}_{pt}\,.$$

The tariff is

$$\begin{aligned} T_{pt}(\theta_{it}, \eta_{kt}, \nu_{it}) = {} & MF_{pt} \\ & + \mathbf{1}\{B_2(\theta_{it} \leq \eta_{kt} + \nu_{it} < B_3(\theta_{it})\} \left[\bar{p}^O_{pt} N_t e^{\theta_{it} + \eta_{kt} + \nu_{it} - \alpha b \bar{p}^O_{pt}} - p^O_{pt} a^O_{pt}\right] \\ & + \mathbf{1}\{B_3(\theta_{it} \leq \eta_{kt} + \nu_{it} < B_4(\theta_{it})\} \bar{p}^O_{pt} N_t \left(\frac{a^I_{pt}}{N^I_{pt}} - \frac{a^O_{pt}}{N^O_{pt}}\right) \\ & + \mathbf{1}\{\eta_{kt} + \nu_{it} \geq B_4(\theta_{it})\} \left[\bar{p}_{pt} N_t e^{\theta_{it} + \eta_{kt} + \nu_{it} - \alpha b \bar{p}_{pt}} - p^O_{pt} a^O_{pt} - p^I_{pt} a^I_{pt}\right]. \end{aligned}$$



Note: Consumers cannot recognize the carrier of a phone receiver in the simulation.

Figure 6: Simulated market concentration rates with carrier recognizability

The surplus from calling is

$$
\begin{aligned}
\mu_{pt}(\theta_{it},\eta_{kt},\nu_{it}) = -\alpha MF_{pt} &+ \mathbf{1}\{\eta_{kt}+\nu_{it}<B_1\}\left[\frac{N_t}{b}e^{\theta_{it}+\eta_{kt}+\nu_{it}}\right] \\
&+ \mathbf{1}\{B_1 \le \eta_{kt}+\nu_{it}<B_2\}\frac{N_t a^O_{pt}}{bN^O_{pt}}\left[\theta_{it}+\eta_{kt}+\nu_{it}+1-\log\left(\frac{a^O_{pt}}{N^O_{pt}}\right)\right] \\
&+ \mathbf{1}\{B_2 \le \eta_{kt}+\nu_{it}<B_3\}\left[\frac{N_t}{b}e^{\theta_{it}+\eta_{kt}+\nu_{it}-\alpha b p^O_{pt}}+\alpha p^O_{pt}a^O_{pt}\right] \\
&+ \mathbf{1}\{B_3 \le \eta_{kt}+\nu_{it}<B_4\}\frac{N_t a^I_{pt}}{bN^I_{pt}}\left[\theta_{it}+\eta_{kt}+\nu_{it}+1-\log\left(\frac{a^I_{pt}}{N^I_{pt}}\right)-\alpha N_t\bar{p}^O_{pt}\left(\frac{a^I_{pt}}{N^I_{pt}}-\frac{a^O_{pt}}{N^O_{pt}}\right)\right] \\
&+ \mathbf{1}\{\eta_{kt}+\nu_{it}\ge B_4\}\left[\frac{N_t}{b}e^{\theta_{it}+\eta_{kt}+\nu_{it}-\alpha b p^O_{pt}}+\alpha\left(p^O_{pt}a^O_{pt}+p^I_{pt}a^I_{pt}\right)\right].
\end{aligned}
$$

Table 11 compares the actual outcome with the simulated one. Consumers are slightly worse off when they cannot recognize the carrier of a phone receiver. The average expected consumer surplus drops by 0.6%. The market shares are more evenly distributed among carriers. Chunghua Telecom loses 3.7% of subscribers while Mo Bi Tai gains 3.5%. As Figure 6 shows, there is a small decrease in the HHI. The median change in HHI over time is 33 points. The quartiles are 29 and 37

Table 11: Counterfactual simulation on carrier recognizability

	Actual	Simulated
Average Usage (minutes)	43.17	42.78
Average Expenditure (TWD)	306.79	307.93
Average Expected Consumer Surplus (TWD)	203.60	202.34
Number of Subscribers (millions)		
CHT	3.8151	3.6725
TCC	2.6816	2.6885
FET	2.0449	2.0452
KGT	1.6937	1.7274
TAT	1.0154	1.0487
MBT	0.3276	0.3390
Total	11.5783	11.5214
Aggregate Volume (million minutes)		
CHT	338.45	326.07
TCC	217.29	218.29
FET	162.45	161.97
KGT	191.93	191.93
TAT	45.12	47.35
MBT	20.51	21.34
Total	975.75	966.95
Revenue (billion TWD)		
CHT	2.5139	2.4524
TCC	1.5639	1.5790
FET	1.2456	1.2511
KGT	1.0417	1.0814
TAT	0.3916	0.4122
MBT	0.1780	0.1846
Total	6.9348	6.9607

Note: Calculated for December of 2003.

points. The intuition for the simulation result is simple. Because consumers cannot adjust volumes according to the termination of a phone call, intra-network discounts are less effective in altering the market structure.

Combing the simulated results in this section with those in Section 7.1, the "tipping effects" on the market shares due to termination-based price discrimination are slightly smaller when the carrier of a phone number cannot be easily identified. Therefore, even in a cellular market like the U.S., where the carrier is not recognizable from a phone number, intra-network discounts are still likely to have large effects in the market structure. In addition, since the effects due to carrier recognizability are modest, carriers do not have a strong incentive to help their customers to know the terminating network of a phone call.

8 Conclusion

In the telecommunications industry, firms often provide a menu of optional rate plans. Because plan choice and volume choice are temporally separated, consumers can adjust their behaviors after learning new information. This paper develops a framework to analyze such an environment. Because consumers choose different quantity of the service, market shares measured by the number of subscribers differ from those computed from the traffic volume. I combine these two measures of market shares in the estimation to identify consumers' two-stage decisions on plan and volume. Moreover, household survey data are incorporated to improve the identification of consumer heterogeneities. Moment conditions are derived from a preference-based structural model. I apply the method to analyze the Taiwanese cellular market. Consumers differ vertically in their utility of using cellular service even after controlling for the income variation. Meanwhile, the perceived product qualities are substantially differentiated. Conditional on subscription, Chunghua Telecom has the highest perceived signal quality. The two regional carriers, Mo Bi Tai and Trans Asia, have the lowest. However, for a given surplus from calling, Trans Asia is the most attractive subscription choice, but Chunghua Telecom is the least one. Consequently, it is important to account for these heterogeneities in empirical analyses of this cellular market. I use the estimated model to evaluate the effect of termination-based price discrimination. Intra-network discounts substantially increase the concentration rate in this highly concentrated market. The HHI increases 264 points on average. Being able to recognize the carrier of a phone number has a positive effect on the concentration rate, but its effect is modest.

This paper focuses on consumer demand, taking price schedules as given. A more comprehensive analysis in the future would include carriers' pricing decision. Furthermore, the static framework neglects switching costs. A dynamic model should account for inter-temporal consideration on the subscription choices.

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