Market Entry and Network Investment

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1 Introduction

We examine the impact of market entry on incumbent's investment in the network quality of the mobile telecommunications services in France. Upon entry in 2012, the fourth mobile operator, *Free mobile*, has triggered an intensified price competition by offering high speed mobile data services at low cost. The new competition has undoubtedly led to increased consumer surplus in the short term. However, the more important question in the social welfare perspective is how it has affected the incumbent's incentives to invest in the product technology.

The issue of competition and innovation has been under debate long since the seminal works of Arrow (1962) and Gilbert and Newbery (1982), who predict opposite directions for the incumbent's investment in the post-entry market. More recently, Aghion et al. (2005) and Aghion et al. (2009) provide empirical evidence that suggest a complex nonlinear relationship between competition and innovation, which likely depends on various factors including market power, nature of innovation, and technological states of the firms. Instead of cross-industry analysis, Goettler and Gordon (2011) focus on a particular durable good industry to find that competition lowers the incumbent's investment. However, it is unclear whether the same conclusion will hold for telecommunications services that lack the product durability, which is found by Goettler and Gordon (2011) as an important driver for the incumbent's innovation to create new demand.

In this paper, we develop a dynamic oligopoly model of network investment to examine the impact of entry on the incumbent's incentives for investment in 3G mobile network infrastructure. The model is characterized by mobile networks maximizing the net present value of expected profit flows by choosing optimal pricing and investment strategies under convex cost of network investment. The model framework builds on the Markov perfect equilibrium framework of Ericson and Pakes (1995) and Doraszelski and Satterthwaite (2010) following the empirical literature on entry and capacity investment (Ryan, 2012; Collard-Wexler, 2013) and product quality race (Goettler and Gordon, 2011).

2 Data

We collect data on consumer demand for mobile services in France during 2011-2013 from Kantar. The data consists of prices, subscribed operators, type of service contracts (e.g., prepaid, postpaid), service attributes (e.g., allowances for voice, data, and text), and demographics (geographical location) of approximately 6,000 consumers for each month. The data provides information on the individual-level subscription choices for three incumbent mobile network operators (Orange, SFR, and Bouygues) and their subsidiary product lines (Sosh, RED, B&You), respectively. The data covers 22 *régions* in mainland France, which are administrative areas excluding the overseas regions. The launch of the subsidiary brands were observed in the sample around the time of Free mobile's entry. The data also includes MVNO operators, which we group into categories based on the parent networks.

We measure the network investment by the number of cellular antenna sites newly installed by mobile operators in each local region. We collect information on the location, the date of activation, the technology generation (2G, 3G, and 4G), and the frequency of antennas from *L'Agence nationale des fréquence* (ANFR), a public authority that governs the operation of radio communications facilities. The size of antenna network is an important determinant of the radio signal strength and the data transmission speed, and also commands a major part of expenditures for the mobile operators building a network. Hence, we use the antenna network size to represent the network investment.

We obtain information on the market size from the population data provided by the national statistics agency, *L'Institut national de la statistique et des études économiques* (INSEE).

3 Model

3.1 Consumer demand

We employ a simple logit framework of discrete choice demand for differentiated products (Berry, 1994). Suppose that consumer h receives utility u_{hit} from firm i's service at time period t specified as

$$u_{hit} = \gamma A_{it} - \alpha p_{it} + \xi_{it} + \epsilon_{hit}, \tag{1}$$

where A_{it} is the quality index of firm i's mobile network measured by the total number of antennas A_{it}, p_{it} is the price, ξ_{it} is the mean quality net of price and network quality that may contain other firm- and time- specific differentiated characteristics (not necessarily identical to Berry's (1994) "unobserved demand shock"), and ϵ_{hit} is random taste varying across individuals, products, and time periods. Then the total demand of firm i at time t is

$$D_{it} = M \frac{e^{\delta_{it}}}{\sum_{j=0}^{N} e^{\delta_{jt}}}, \tag{2}$$

where $\delta_{it} = \gamma A_{it} - \alpha p_{it} + \xi_{it}$, and M is the total population of the corresponding region.

3.2 States and transition

Suppose that there are $N = 1$ single-product networks indexed by $i = 0, 1, ..., N$. At given time period t, the immediate payoff of firm i is characterized by a state vector $s_{it} \in \mathcal{S}_i$, where $\mathcal{S}_i$ is the state space. The state of firm i is defined by endogenous network quality A_{it} and vector of exogenous state variables x_{it} that includes product quality ξ_{it} and marginal cost c_{it}.

Under this notation, the market is completely characterized by the collection of states $s_t = (A_t, x_t) \in \mathcal{S} = S_0 \times \cdots S_N$, where $A_t = (A_{0t}, ..., A_{Nt})$. Since the firm's payoff is invariant with respect to translation in A_t, can be denoted as $\tilde{A}_t = (A_{1t} - A_{0t}, ..., A_{Nt} - A_{0t}) \in \mathcal{S}_1 \times \cdots \mathcal{S}_N$ without loss of generality.

We assume that the evolution of A_t follows a deterministic rule. Specifically, it is the cumulative sum of all network investments:

$$A_{it+1} = A_{it} + a_{it}, \qquad i = 0, 1, ..., N. \tag{3}$$

The evolution of the exogenous state x_{it} is assumed to follow a stationary first-order Markov process $F(x_{it+1}|x_{it})$ that is absolutely continuous with respect to the Lebesgue measure.

3.3 Firm's decision

The one-period profit of firm i given state s_t and actions $(p_t, a_t) \in \mathcal{A}$ is

$$\pi_i(s_t, p_t, a_{it}) = (p_{it} - c_{it}) D_i(s_t, p_t) - C(a_{it}), \tag{4}$$

where D_i is the demand function of firm i in Equation 2, and $C(a_{it})$ is the cost of adjusting network capacity by the amount of a_{it}, which may also contain a non-zero fixed cost of adjustment. Given the network size A_{it} and other payoff-relevant states x_{it} at given time period t, the firms simultaneously set the level of price and investment to maximize the net present value of expected profit flows over infinite horizon. After the decisions are made, the firms receive revenue net of investment cost, and the network size and other states for the next period are determined. The firms have complete information on the current state when making the decisions. We focus on the stationary Markov strategy where the firm's decisions depend on the current state only rather than the entire history of the game.

For each given state s_t at time t, firm i sets optimal strategies $\{p^*_{is}, a^*_{is}\}_{s=t}^{\infty}$ that maximize the expected net present value of profit flows over infinite horizon conditional on the actions of all other firms $(p_{-it}, a_{-it}) \in \mathcal{A}_{-i}$. This is formally defined as value function $V(s_t)$:

$$V_i(s_t) = \max_{\{p_{i\tau}, a_{i\tau}\}_{\tau=t}^{\infty}} \sum_{\tau=t}^{\infty} \beta^{\tau-t} \mathrm{E}\big[\pi_i(s_\tau, p_{i\tau}, p_{-i\tau}, a_{i\tau}) | s_t, p_t, a_t\big], \tag{5}$$

where p_{-it} denotes the price vector for the competitors of firm i, and E is the expectations operator for the joint conditional distribution of $s_\tau = (A_\tau, x_\tau)$ given states $s_t = (A_t, x_t)$ and actions (p_t, a_t) for $\tau = t, ..., \infty$. The firms are assumed to form a rational expectation on the state transition distribution $F(s_{t+1}|s_t, a_{it}, a_{-it})$. In equilibrium, the value function satisfies the Bellman equation:

$$V_i(s_t) = \max_{p_{it}, a_{it}} \left[\pi_i(s_t, p_{it}, p^*_{-it}, a_{it}) + \beta \int V_i(s_{t+1}) \mathrm{d}F(s_{t+1}|s_t, a_{it}, a^*_{-it})\right], \tag{6}$$

where (p^*_{-it}, a^*_{-it}) is the best response to (p_{it}, a_{it}).[1] Since p_t does not affect the future state, it is omitted in the state transition distribution $F(s_{t+1}|s_t, a_t)$, which implies a static price competition. The Markov perfect equilibrium (MPE) strategy is a subgame perfect Nash equilibrium that maps payoff-relevant state space $\mathcal{S}$ to action space $\mathcal{A}$: $(p^*_{it}, a^*_{it}) = \big(p_i(s_t), a_i(s_t)\big)$ for all $i = 1, ..., N$. The existence of MPE in dynamic game with continuous actions is established by Escobar (2013).

To reduce the computational burden, the literature typically assumes that the payoff function is homogeneous for the firms conditional on the state, so as to solve for a symmetric MPE strategy (p^*_t, a^*_t), instead of N strategy functions (or correspondences in case of multiple equilibria).

4 Empirical strategy

The estimation proceeds in three steps. In the first stage, we estimate the demand model using a simple logit regression. Given the demand function estimate, the second stage solves for the marginal cost from the first-order condition of the static profit maximization problem. The last step uses all the estimates obtained in the previous stages to recover the cost function parameters.

In the first stage, we use an instrumental variables regression following Berry (1994) to estimate the demand system

$$\log(D_{it}/D_{0t}) = \gamma A_{it} - \alpha p_{it} + \xi_{it}. \tag{7}$$

[1] Given any opponent strategy (p_{-it}, a_{-it}), the value function is a unique solution to the Bellman equation by Bellman's principle of optimality under certain regularity conditions (Rust, 1988). However, there could exist multiple sets of equilibrium strategy profile satisfying the above Bellman equation.

For estimating the marginal cost, we follow the standard practice of the literature (Nevo, 2001) since the pricing is nested within the network investment decision. Specifically, we use the first-order condition

$$(p_{it}^* - c_{it})D_i'(s_t, p_t^*) + D_i(s_t, p_t^*) = 0, \qquad i = 1, ..., N, t = 1, ..., T. \tag{8}$$

Given the demand primitives and the marginal cost estimates, we can estimate the state transition distribution $F(x_{t+1}|x_t)$ using a simple first-order autoregressive model: $x_{t+1} = \phi_0 + \phi_1 x_t + \eta_t$, where η_t is an independently distributed random shock.

For the cost structure, we assume a quadratic cost function

$$C(a_{it}) = \lambda_1 a_{it} + \lambda_2 a_{it}^2, \tag{9}$$

where λ_1 and λ_2 capture convex adjustment cost.

4.1 Estimation of network investment costs

We adopt a stochastic Euler equation approach for the estimation of the adjustment cost function. It is first proposed by Hansen and Singleton (1982) for estimating general dynamic models with continuous control variables. The continuity of the control and state variables makes the approach a suitable choice for our estimation as the firm's dynamic investment problem can be represented by stochastic Euler equations.

Formally, the Euler equation can be derived from the Bellman equation by using the first-order condition and the envelope theorem (Rust, 1996). Define a profit function evaluated at the equilibrium prices p_t^*: $\pi^0(s_t, a_t) = \pi(s_t, p_t, a_t)$. Then for the observed states s_t and investment choices a_t, we obtain

$$\frac{\partial \pi_i^0(s_t, a_t)}{\partial a_{it}} + \beta \mathrm{E}_{x_{t+1}} \left[\frac{\mathrm{d}\pi_i^0(\tilde{A}_{t+1}, x_{t+1}, a_{it+1})}{\mathrm{d}A_{it+1}} - \frac{\partial \pi_i^0(\tilde{A}_{t+1}, x_{t+1}, a_{it+1})}{\partial a_{it+1}} \middle| x_t \right] = 0, \tag{10}$$

for $1 \leq i \leq N$, while for firm 0, the equation takes the following form

$$\frac{\partial \pi_0^0(s_t, a_t)}{\partial a_{0t}} - \beta \sum_{i=1}^{N} \mathrm{E}_{x_{t+1}} \left[\frac{\mathrm{d}\pi_i^0(\tilde{A}_{t+1}, x_{t+1}, a_{it+1})}{\mathrm{d}A_{it+1}} - \frac{\partial \pi_i^0(\tilde{A}_{t+1}, x_{t+1}, a_{it+1})}{\partial a_{it+1}} \middle| x_t \right] = 0, \tag{11}$$

for firm 0 (see appendix for derivation).[2] By substituting with the model primitives and reordering the terms,

[2] The Euler equation is derived under a certain assumption on the equilibrium, which does not hold in general dynamic games as noted by Pakes (1996). However, we conjecture that our particular model permits the use of the Euler equation, which we plan to show in the upcoming version of the draft.

we can obtain the Euler equation

$$\mathrm{E}_{x_{t+1}}\left[-C'(a_{it})+\beta\left(\frac{\mathrm{d}\pi_i^0(A_{t+1},x_{t+1},a_{it+1})}{\mathrm{d}A_{it+1}}+C'(a_{it+1})\right)\Bigg|x_t\right]=0, \tag{12}$$

for $i=1,...,N$ and $t=1,...,T-1$ at the observed sample of $\{(p_t,a_t)\}_{t=1}^T$ and the parameter estimates in the profit function.[3]

The advantage of the Euler equation representation is that it does not have to compute the value function even in an approximate form, in contrast to the alternative representations that use forward simulation or various other methods to at least approximately evaluate the value function (e.g., Bajari et al. (2007)). By circumventing the need for explicit solution of the value functions and the optimal decision rules, this approach is expected to greatly reduce the approximation bias as well as the computational burden in the estimation, particularly in dynamic games with continuous controls and states.

However, the Euler equation involves the expected value of an equation containing $(t+1)$-period equilibrium prices p_{t+1} and optimal investment a_{it+1} conditional on the information of x_t. The key observation of Hansen and Singleton (1982) is to form a set of orthogonality conditions using instruments predetermined (but not necessarily exogenous) as of time period t. Let $\theta=(\lambda_1,\lambda_2)$ denote the parameters of the cost function. For the true parameter vector $\theta_0\in\mathcal{R}^2$ and the instrument vector $z_t\in\mathcal{R}^L$, the orthogonality condition can be formulated by taking iterative expectations as

$$\mathrm{E}\big[h(s_t,s_{t+1},\theta_0)\otimes z_t\big]=\mathbf{0}, \tag{13}$$

where E is the unconditional expectations operator with respect to (s_t,s_{t+1}), $\otimes$ denotes the Kronecker product operator, $h=(h_1,...,h_N)$, where each function h_i is defined as

$$h_i(s_t,s_{t+1},\theta)=-C'(a_{it};\theta)+\beta\left(\frac{\mathrm{d}\pi_i(s_{t+1},p_{it+1},a_{it+1})}{\mathrm{d}A_{it+1}}+C'(a_{it+1};\theta)\right). \tag{14}$$

Hansen and Singleton (1982) propose a generalized method of moment (GMM) estimator for the class of models that permit moment conditions as Equation 13. They highlight that the GMM estimator is flexible in the choice of z_t (e.g., current and lagged state variables) and is robust to the case of serially correlated moments and endogenous instruments.

[3] The Euler equation can be evaluated only up to $t=T-1$ due to the one-period forward term in the bracket.

5 Estimation results

Table 1 presents the demand estimation results. We account for price endogeneity by including antenna-based instruments analogous to Berry et al. (1995). However, it has little effect on the price coefficient.

We find insignificance in the coefficient of 4G antennas. Since we do not observe the commercial launch date of the 4G networks at region level, we use an ad hoc estimate for the availability of the service for all the regions based on media announcements. This measurement error could have led to the relatively large standard error. The strongly negative coefficient for 2G antennas may arise from various reasons not accounted for in the model. We abstract away from 2G investment since it has reached a stationary level as of the observation period.

	OLS	IV
Price	-0.0843***	-0.0826***
	(0.000)	(0.000)
Call allowance	0.5055***	0.5009***
	(0.000)	(0.000)
Data allowance	0.3441***	0.3260***
	(0.000)	(0.000)
Text allowance	-0.0031	0.0057
	(0.904)	(0.851)
Total antenna 2G	-0.0243**	-0.0239**
	(0.007)	(0.002)
Antenna 3G	0.0631***	0.0633***
	(0.000)	(0.000)
Total antenna 4G	0.0170	0.0207
	(0.585)	(0.466)
Antenna 3G roaming	0.0487***	0.0469***
	(0.000)	(0.000)
Orange	4.0105***	3.9746***
	(0.000)	(0.000)
SFR	3.1623***	3.1352***
	(0.000)	(0.000)
Bouygues	2.9523***	2.9194***
	(0.000)	(0.000)
Free	-0.0972	-0.0222
	(0.606)	(0.940)
Sosh	-0.9989***	-0.9984***
	(0.000)	(0.000)
B&You	-1.2302***	-1.2036***
	(0.000)	(0.000)
Red	-1.3884***	-1.3866***
	(0.000)	(0.000)
Virgin	0.6749***	0.7109***
	(0.000)	(0.000)
MVNO (Orange+SFR)	0.0412	0.0762
	(0.658)	(0.504)
MVNO (Orange)	0.0318	0.0630
	(0.805)	(0.680)
MVNO (SFR)	0.6232***	0.6562***
	(0.000)	(0.000)
Time trend	0.0951***	0.0975***
	(0.000)	(0.000)
Constant	-19.3100***	-19.8638***
	(0.000)	(0.000)
Observations	2070	2070
R-squared	0.781	0.781
Adjusted R-squared	0.779	0.779
Overid test (p-value)	–	0.2829

p-values in parentheses

Table 1: Estimation of consumer demand for mobile services

Using the demand estimation results, we recover the marginal costs from the first order condition implied by the second stage pricing game following Nevo (2001). Table 2 presents the average marginal costs across time periods and regions by each mobile operator. For simplicity, we assume that pricing decisions are independently made across regions in order to express the derivatives in a closed form, though it would be straightforward to relax the assumption.

Operator	Price (€)	Marginal costs (€)	Lerner index
Orange	25.011	5.965	0.813
SFR	22.810	6.761	0.741
Bouygues	23.462	8.879	0.784
Free	13.059	-0.474	1.047
Virgin	19.965	7.326	0.638
MVNO: Orange+SFR	25.443	13.12	0.497
MVNO: Orange+SFR	17.035	4.761	0.761
MVNO: SFR	12.904	0.317	1.001
MVNO: Bouygues	33.178	20.935	0.423

Table 2: Estimation of average marginal production costs by operators

Based on the marginal cost estimates, we turn to the estimation of the network investment costs. We focus on investment decisions on 3G antenna networks since it is difficult for us to obtain reliable estimates on the consumer valuation of 2G and 4G networks in the demand estimation.

First, we slightly modify the supply model to estimate myopic firm's investment costs. Table 3 shows the estimates for the investment cost function specified in Equation 9 in Column 1. The antenna coefficients indicate that it costs about 46,420 €(=1*29,205 + 1^2*17,215) to build 100 additional antennas in a region.

Columns 2-4 further relax the homogeneity assumption by including firm, region and time specific heterogeneity. Column 2 sets the fixed effect for Free mobile to zero and finds significant cost difference between firms. Including population yields cost estimates inconsistent with the intuition while linear time trend has no significant result.

In dynamic cost model estimation, we observe an overall similar pattern. Table 4 presents results using different set of instruments and cost function specifications with the discount factor β=1. For the instruments, we use current and lagged 3G antennas, mean product quality net of price and antennas, and marginal costs in Columns 1-2. Columns 3-5 adds lagged BLP-type instruments based on 3G antennas, and Column 6 also includes current and lagged shares of networks in addition to all the instruments.

The biggest difference with the static estimation results is that the coefficient of Antenna/100 is scaled by 1-β, such that it needs to multiplied by 100. Hence, under the dynamic investment model, we obtain more realistic estimate on the cost of investment.

	(1)	(2)	(3)	(4)
Antenna/100	29205.92***	12524.60***	-16388.39***	11819.66***
	(0.000)	(0.000)	(0.000)	(0.000)
$(\text{Antenna}/100)^2$	17215.12**	17568.29***	-1280.62**	17592.34***
	(0.001)	(0.000)	(0.003)	(0.000)
Orange		29910.27***	27906.00***	29946.84***
		(0.000)	(0.000)	(0.000)
SFR		17718.98***	16613.03***	17735.34***
		(0.000)	(0.000)	(0.000)
Bouygues		10279.69***	8337.10***	10322.61***
		(0.000)	(0.000)	(0.000)
Population			0.01***	
			(0.000)	
Time trend				138.89
				(0.737)
Observations	1059	1059	1059	1059
R^2	0.077	0.175	0.956	0.176
Adjusted R^2	0.076	0.172	0.956	0.172
F	14.63	56.07	4627.66	44.84

p-values in parentheses
Fixed effect for Free mobile is set to 0.

Table 3: Estimation of static investment cost model

	(1)	(2)	(3)	(4)	(5)	(6)
$(1\text{-}\beta)\cdot$Antenna/100	26447.04***	18683.61***	18483.03***	21447.15***	-14706.77***	20942.32***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$(\text{Antenna}/100)^2$	6863.17**	4730.86	5179.16	8979.30**	-2588.41***	7739.42**
	(0.022)	(0.164)	(0.125)	(0.014)	(0.000)	(0.030)
Orange		19437.31***	19619.19***	17064.13***	24566.95***	17439.68***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
SFR		8263.99**	8696.56***	5341.50**	12883.94***	6288.17**
		(0.004)	(0.001)	(0.030)	(0.000)	(0.002)
Bouygues		1813.18	1878.14	-1860.53	5155.91***	-1345.78
		(0.502)	(0.465)	(0.430)	(0.000)	(0.525)
Population					0.01***	
					(0.000)	
Observations	909	909	909	909	909	909
χ^2	5.24	81.99	95.57	76.33	13871.55	114.00

p-values in parentheses; β=0.99.
Fixed effect for Free mobile is set to 0.

Table 4: Estimation of dynamic investment cost model

A Derivation of the Euler equation

When the firms choose investment at optimal prices p_t^* at time t, the Bellman equation (Equation 6) can be written as

$$V_i(s_t) = \max_{a_{it}} \left[\pi_i(s_t, p_t^*, a_{it}) + \beta \int V_i(s_{t+1}) \mathrm{d}F(s_{t+1}|s_t, a_{it}, a_{-it}^*) \right], \tag{15}$$

where $s_t = (\tilde{A}_t, x_t)$, and each element of $\tilde{A}_t$ is given by $\tilde{A}_{it} = A_{it} - A_{0t}$. Note that $\mathrm{d}F(s_{t+1}|s_t, a_{it}, a_{-it}^*) = \mathrm{d}\delta_{\tilde{A}_{t+1}}(\tilde{A}_{t+1} = \tilde{A}_t + a_{-0t} - a_{0t})\mathrm{d}F(x_{t+1}|x_t)$, where $\delta_{\tilde{A}_{t+1}}$ is a Dirac measure on the space of $\tilde{A}_{t+1}$, and $a_{-0t} = (a_{1t}, ..., a_{Nt})$. Then the above equation can be expressed as

$$V_i(s_t) = \max_{a_{it}} \left[\pi_i(s_t, p_t^*, a_{it}) + \beta \int V_i(\tilde{A}_{t+1}, x_{t+1}) \mathrm{d}F(x_{t+1}|x_t) \right], \tag{16}$$

where $\tilde{A}_{t+1}$ is such that $\tilde{A}_{it+1} = \tilde{A}_{it} + a_{it} - a_{0t}$ for $i = 1, ..., N$.

First, we derive Equation 10 for firms $i = 1, ..., N$. Let a_{it}^* denote the solution of the above Bellman equation. Then by the envelope theorem,

$$\frac{\partial V_i(s_t)}{\partial \tilde{A}_{it}} = \frac{\mathrm{d}\pi_i(s_t, p_t^*, a_{it}^*)}{\mathrm{d}\tilde{A}_{it}} + \beta \int \frac{\partial V_i(\tilde{A}_{t+1}, x_{t+1})}{\partial \tilde{A}_{it+1}} \frac{\partial \tilde{A}_{it+1}}{\partial \tilde{A}_{it}} \mathrm{d}F(x_{t+1}|x_t). \tag{17}$$

And by using the first-order condition,[4] we obtain

$$\frac{\partial \pi_i(s_t, p_t^*, a_{it}^*)}{\partial a_{it}} + \beta \int \frac{\partial V_i(\tilde{A}_{t+1}, x_{t+1})}{\partial \tilde{A}_{it+1}} \frac{\partial \tilde{A}_{it+1}}{\partial a_{it}} \mathrm{d}F(x_{t+1}|x_t) = 0. \tag{18}$$

Since $\frac{\partial \tilde{A}_{it+1}}{\partial \tilde{A}_{it}} = \frac{\partial \tilde{A}_{it+1}}{\partial a_{it}} = 1$ for $i = 1, ..., N$, we can combine Equations 16 and 17 to obtain

$$\frac{\partial V_i(s_t)}{\partial \tilde{A}_{it}} = \frac{\mathrm{d}\pi_i(s_t, p_t^*, a_{it}^*)}{\mathrm{d}\tilde{A}_{it}} - \frac{\partial \pi_i(s_t, p_t^*, a_{it}^*)}{\partial a_{it}} \qquad \forall i, t. \tag{19}$$

If Equation 16 holds for all $s_t \in \mathcal{S}$ and $a_{-it} \in \mathcal{A}$, we can use it to substitute the integrand of the first-order condition (Equation 15) to obtain

$$\frac{\partial \pi_i(s_t, p_t^*, a_{it}^*)}{\partial a_{it}} + \beta \int \left[\frac{\mathrm{d}\pi_i(s_{t+1}, p_{t+1}^*, a_{it+1}^*)}{\mathrm{d}\tilde{A}_{it+1}} - \frac{\partial \pi_i(s_{t+1}, p_{t+1}^*, a_{it+1}^*)}{\partial a_{it+1}} \right] \mathrm{d}F(x_{t+1}|x_t) = 0. \tag{20}$$

[4] We note that the literature has avoided making such assumption in a general setting (e.g., Berry and Pakes (2001)). We conjecture that it will hold under our particular model but we plan to verify it in the next revision.

Now, we apply the same derivation for firm 0 to obtain

$$\frac{\partial V_0(s_t)}{\partial \tilde{A}_{it}} = \frac{\mathrm{d}\pi_0(s_t, p_t^*, a_{0t}^*)}{\mathrm{d}\tilde{A}_{it}} + \beta \int \frac{\partial V_0(\tilde{A}_{t+1}, x_{t+1})}{\partial \tilde{A}_{it+1}} \frac{\partial \tilde{A}_{it+1}}{\partial \tilde{A}_{it}} \mathrm{d}F(x_{t+1}|x_t),$$

and Equation 18 becomes

$$\frac{\partial \pi_0(s_t, p_t^*, a_{0t}^*)}{\partial a_{0t}} + \beta \int \sum_{i=1}^{N} \frac{\partial V_0(\tilde{A}_{t+1}, x_{t+1})}{\partial \tilde{A}_{it+1}} \frac{\partial \tilde{A}_{it+1}}{\partial a_{0t}} \mathrm{d}F(x_{t+1}|x_t) = 0.$$

From the above two equations, we obtain

$$\sum_{i=1}^{N} \frac{\partial V_0(s_t)}{\partial \tilde{A}_{it}} = \frac{\partial \pi_0(s_t, p_t^*, a_{0t}^*)}{\partial a_{0t}} + \sum_{i=1}^{N} \frac{\mathrm{d}\pi_0(s_t, p_t^*, a_{it}^*)}{\mathrm{d}\tilde{A}_{it}}$$

since $\frac{\partial \tilde{A}_{it+1}}{\partial A_{0t}} = \frac{\partial \tilde{A}_{it+1}}{\partial a_{0t}} = -1$. Equation 20 becomes

$$\frac{\partial \pi_0(s_t, p_t^*, a_{0t}^*)}{\partial a_{0t}} - \beta \int \left[\frac{\partial \pi_0(s_{t+1}, p_{t+1}^*, a_{0t+1}^*)}{\partial a_{0t+1}} + \sum_{i=1}^{N} \frac{\mathrm{d}\pi_0(s_{t+1}, p_{t+1}^*, a_{0t+1}^*)}{\mathrm{d}\tilde{A}_{it+1}} \right] \mathrm{d}F(x_{t+1}|x_t) = 0.$$

B 3G antenna investment

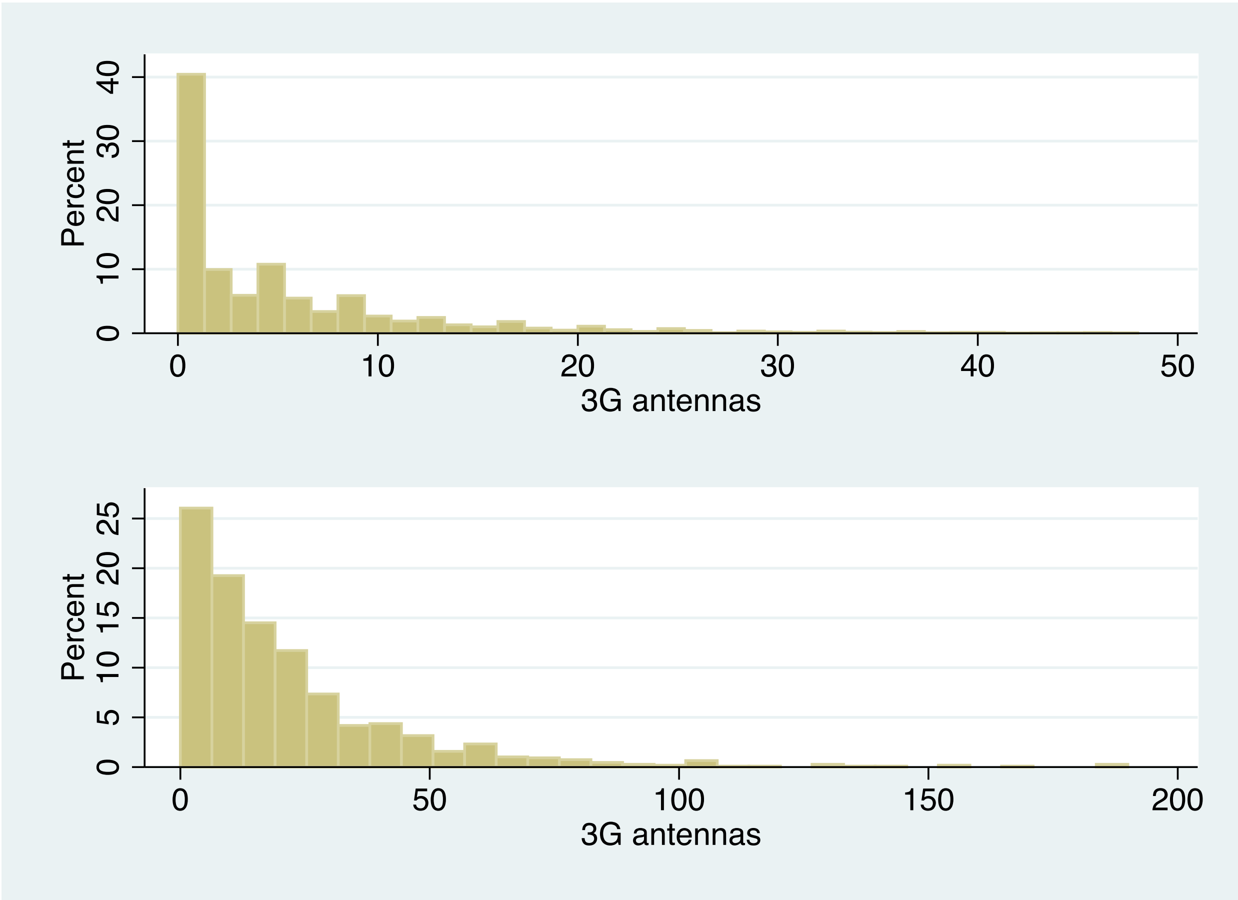

Figure 1: Distribution of new 3G antennas in monthly (top) and quarterly (bottom) samples

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