Market Structure, Investment, and Technical Efficiencies in Mobile Telecommunications

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Motivation

- Horizontal mergers present trade-off between **market power** and **scale efficiencies**
- While making substantial progress on models of demand and market power, antitrust literature has struggled with quantifiation of scale efficiencies

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- Industry argues that consolidation would lead to higher quality of service

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- Worldwide, lots of pressure for telecom mergers, mixed reactions from antitrust agencies
- Industry argues that consolidation would lead to higher quality of service
- Spectrum allocation is a trillion-dollar issue globally

This Paper

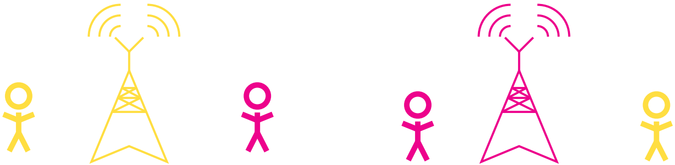
- How does market structure impact equilibrium price, investment, quality, and welfare?
- **Competition in prices and infrastructure**
- A **model of infrastructure and download speeds** based on engineering relationships
  - download speeds a function of infrastructure and demand for data
- A **discrete-continuous choice model**: which mobile service contract to subscribe to, how much data to download
  - demand for data and download speeds simultaneously determined

Preview of Findings

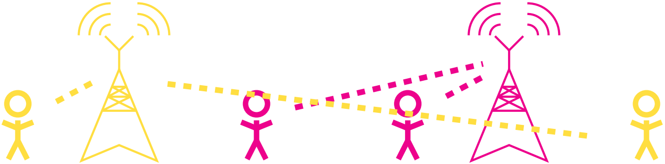
- Engineering models make case for scale efficiencies
  - Scale effficiences from economy of **density** and **pooling**
  - Doesn't put a sign on equilibrium welfare impacts
- 7 firms optimal for consumer surplus; 4 for total surplus
  - Optimal number of firms is higher for low-income consumers
- Marginal consumer surplus from additional spectrum is roughly 5x firm willingness to pay

Economies of Density

Economies of Density



Economies of Density



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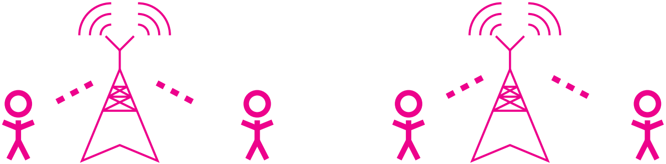

Urban vs. Rural

Economies of Pooling

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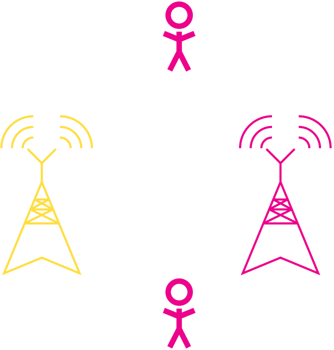

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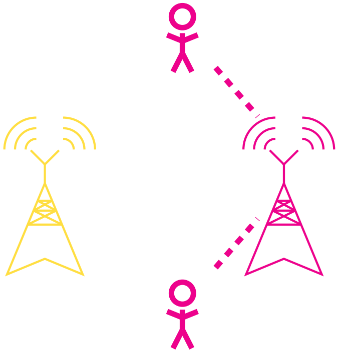
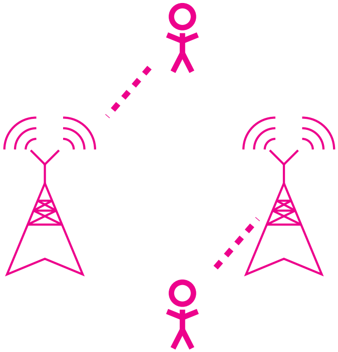


Economies of Pooling



Literature

- **Market power vs. scale efficiencies**: Williamson (1968), Farrell and Shapiro (2000)
- **Market power and antitrust in telecom**: DeGraba and Rosston (2018), Bourreau, Sun and Verboven (2018), Sinkinson (2020)
- **Infrastructure in mobile telecom**: Nevo, Turner, and Williams (2016), Sun (2015), Błaszczyszyn and Karray (2015)
- **Economies of pooling**: "Pooling Principle" in operations literature (Cattani and Schmidt, 2005), Robinson (1948), Baumol (1952), De Vany (1976), Mulligan (1983), Llost, Pinto, and Sibley (2015)
- **Economies of density** (from path loss): Hua, Lu, Panwar (2012), quatification is new in economic model (but discussed in antitrust cases)

French Telecommunications Market

- Four mobile network operators (MNOs)
- Additionally, MNOs share network infrastructure with mobile virtual network operators (MVNOs) History

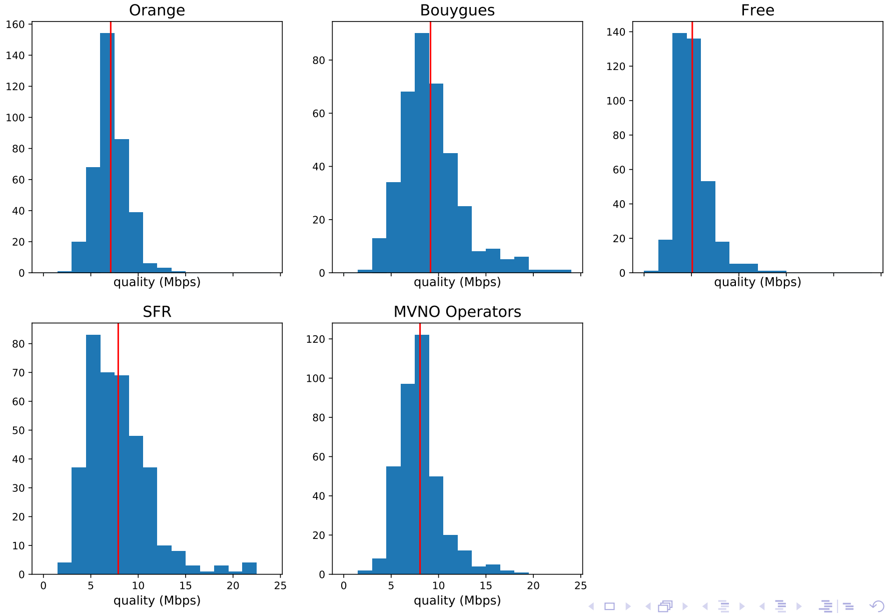
Orange	Bouygues	Free	SFR	MVNO
31.76%	14.12%	14.12%	24.71%	15.29%

- 92% of population above 12 years old are mobile users
- In 2015, 4G technology largely already deployed History
    - Our focus will be mostly on mobile data quality and consumption Usage

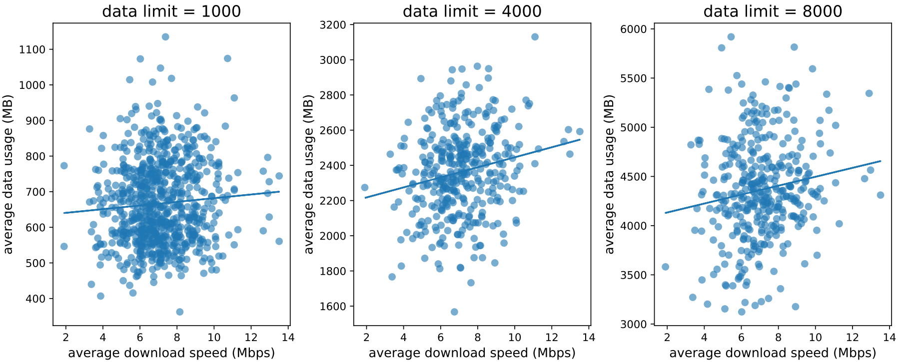
Data

- Detailed municipality-product-level data for all customers from one firm (Orange) ▸▸ Summary Stats
- Aggregate (national) market shares for other firms
- Full menu of contracts for each firm obtained from catalogs
- Firm-municipality download speeds from Ookla
- Demographic information from INSEE
- Detailed infrastructure data (publicly available) from ANFR

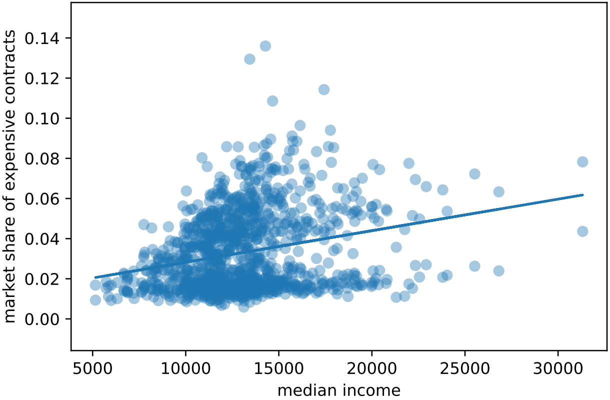
Download Speeds



Demand and Quality



Market Shares and Median Incomes



*expensive contracts defined as those with a price ≥ 30 €

Model Overview

- Model of competition in infrastructure and prices
- Three stages
  1. Firms make infrastructure decisions
  2. Firms choose prices of contracts they offer
  3. Consumers choose plans and data consumption

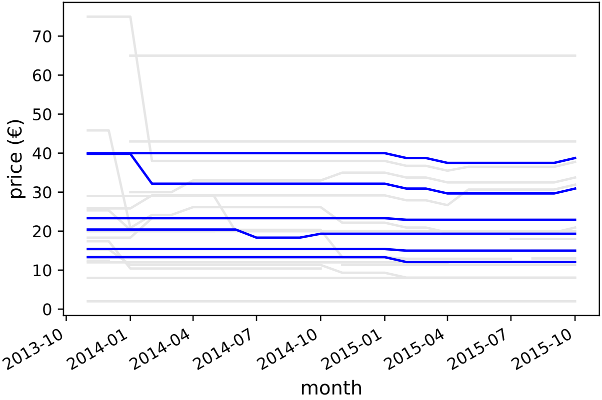
Demand

Demand Model (very briefly)

- Discrete-continuous choices
  - Choice of how much data consumption, based on download speeds, data limit, consumer type, and an idiosyncratic monthly shock
  - Choice of firm and contract anticipating optimal data consumption
- Utility function has terms for price, value of data consumption, dummy for unlimited voice allowance
- Mixed nested logit
  - Coefficients on price, value of data are function of income
  - Outside option has its own nest

Details

Price Variation?



Blue lines are prices for Orange's products

Elasticity Imputations

- Given lack of price variation, it's difficult to estimate a price elasticity
- We impute price elasticities as moments, and we run the demand estimation over a range of imputations $\mathcal{E}$
  - Today: elasticity when Orange changes all prices together is -2.5 based on Bourreau, Sun, and Verboven (2021)

Extended BLP Contraction Mapping

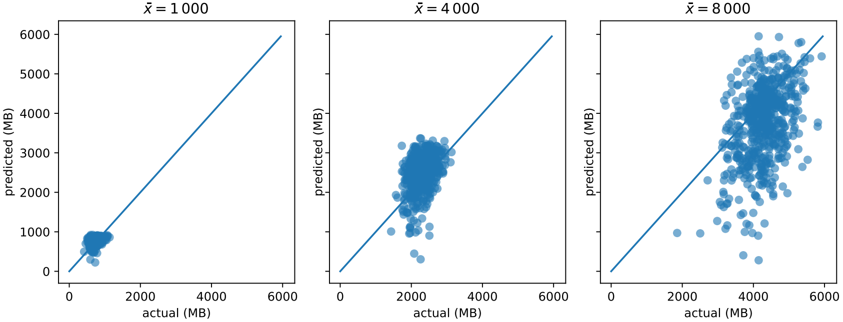
- Choice set includes products for all firms, but we only have **product-level market shares** for Orange
- **Strategy**: model predicts market shares for all products, but we try to rationalize only aggregate market shares for non-Orange firms
- That means we have product- and commune-level shocks ξ_{jm} for Orange products, and $\xi_{jm} = \xi_f$ for non-Orange products
- We show that the BLP contraction mapping still works in this context

Identification

- Imputed elasticities help to identify price coefficient
  - Heterogeneity identified (intuitively) by variation in market shares of expensive plans along with variation in income distribution
- Matching predicted data consumption to observed data consumption helps to identify data utility function
  - Variation in data consumption across median incomes helps to identify heterogeneous component

Moments

Data Consumption Prediction



Willingness to Pay

For 4 GB instead of 1 GB plan:

Elasticity	10th %ile	30th %ile	50th %ile	70th %ile	90th %ile
−2.5	2.51 €	3.05 €	3.53 €	4.12 €	5.40 €

For 20 Mbps instead of 10 Mbps:

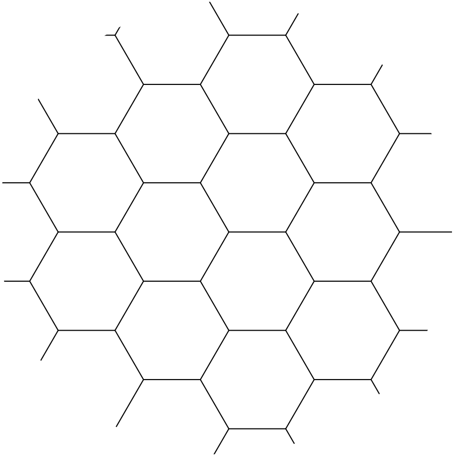
Elasticity	10th %ile	30th %ile	50th %ile	70th %ile	90th %ile
−2.5	1.94 €	2.53 €	3.10 €	3.85 €	5.67 €

Supply

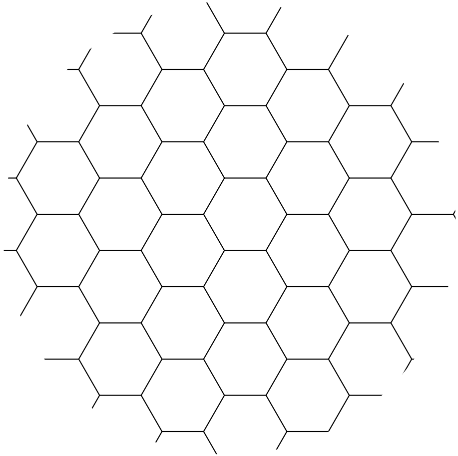
Infrastructure Model

- Firm f endowed with bandwidth (spectrum) B_f
- **Choice variable**: number of base stations N_{fm} (continuous) determines the density of base stations for f in municipality m
- Each base station serves an **equally sized hexagonal cell**
- Size of each base station's cell is $A_{fm} = A_m / N_{fm}$
  Note: full coverage of land area

Density of Cells



Density of Cells



Engineering Model

- **Channel capacity**: maximum download speed $\bar{Q}_{fm} = \bar{Q}\left(B_f, A_m/N_{fm}\right)$ (speed attained if no congestion)
  - increasing (linearly) in B_f
  - increasing in N_{fm} (decreasing in A_m/N_{fm}).
  - based on information theory (Shannon-Hartley Theorem), Hata model of path loss (exponent of 3.52), taking harmonic mean over cell, Details and accounting for interference
- **Congestion**: the amount of data requested, Q^D_{fm}, reduces delivered download speeds Q_{fm}. Assuming M/M/1 queue,

$$Q_{fm} = \bar{Q}_{fm} - Q^D_{fm}$$

  - Q^D_{fm} will come from demand model
  - Q_{fm} and Q^D_{fm} form a simultaneous system

Engineering Model

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- **Congestion**: the amount of data requested, Q_{fm}^D, reduces delivered download speeds Q_{fm}. Assuming M/M/1 queue,

$$Q_{fm}\left(\bar{Q}_{fm}, Q^D\right) = \bar{Q}_{fm} - Q_{fm}^D\left(\mathbf{Q}_m\right)$$

  - Q_{fm}^D will come from demand model
  - Q_{fm} and Q_{fm}^D form a simultaneous system

Firm's Costs

Firms pay two types of costs:

- Cost per base station $c_{fm}B_f$ that is proportional to bandwidth
- A unit cost per consumer c_j^u

Competition in Price

- Firms compete in both prices and infrastructure
- In the second stage, conditional on infrastructure $(\mathbf{N}, \mathbf{B})$, firms compete in prices

$$\mathbf{P}_f^*(\mathbf{N}_m, \mathbf{B}) = \arg\max_{\mathbf{P}_f} \sum_m (\mathbf{P}_f - \mathbf{c}_f^u)\, \mathbf{s}_f(\mathbf{P}_f, \mathbf{P}_{-f}, \mathbf{Q}_m)$$

subject to

$$\forall f, m: \quad Q_{fm} = Q_{fm}\left(N_{fm}, B_f, Q_{fm}^D(\mathbf{P}_f, \mathbf{P}_{-f}, \mathbf{Q}_m)\right)$$

- The $\mathbf{s}_f(\cdot)$ and $Q_{fm}^D(\cdot)$ functions come from the discrete-continuous model of contract choice and data consumption
- Equilibrium download speeds depend on prices
  Result: lower price elasticities with simultaneous determination of demand and quality

Competition in Infrastructure

- In first stage, firms choose N_{fm} to maximize

$$N^*_{fm}(\mathbf{B}) = \arg\max_{N_{fm}} \Big\{ \Pi_f \left(\mathbf{P}^* \left(N_{fm}, \mathbf{N}_{-fm}, \mathbf{B} \right), N_{fm}, \mathbf{N}_{-fm}, \mathbf{B} \right) \\ - C_f \left(B_f, N_{fm} \right) \Big\}$$

  where $\Pi_f(\cdot)$ is the profit function for firm f from the second stage in which firms choose prices conditional on infrastructure

- Average of estimated $\hat{c}^u_j$: Details
  - 8.90 € for products with data limit $<$ 5GB
  - 19.92 € for products with data limit $\geq$ 5GB
- Average of estimated $\hat{c}_{fm} B_f$: 190K € Details

Counterfactuals

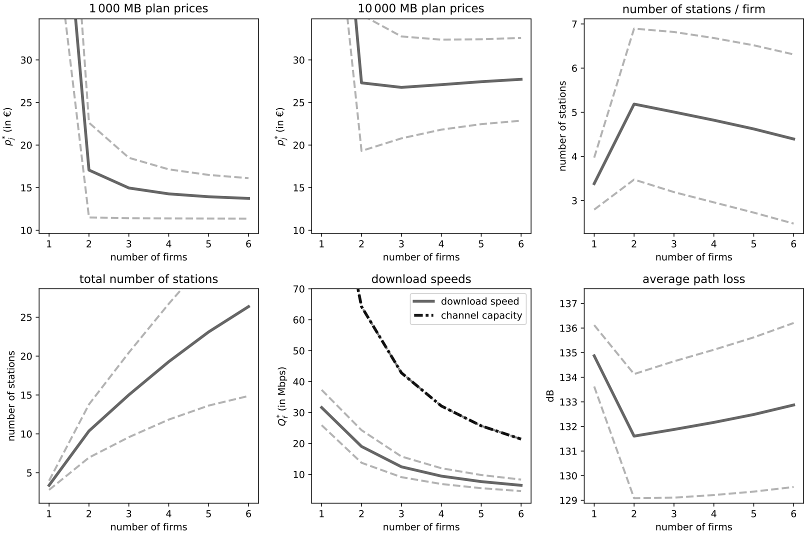
Counterfactuals

- Varying number of firms
- Allocating more spectrum to mobile telecom
- How to allocate new spectrum within mobile telecom

Varying Number of Firms

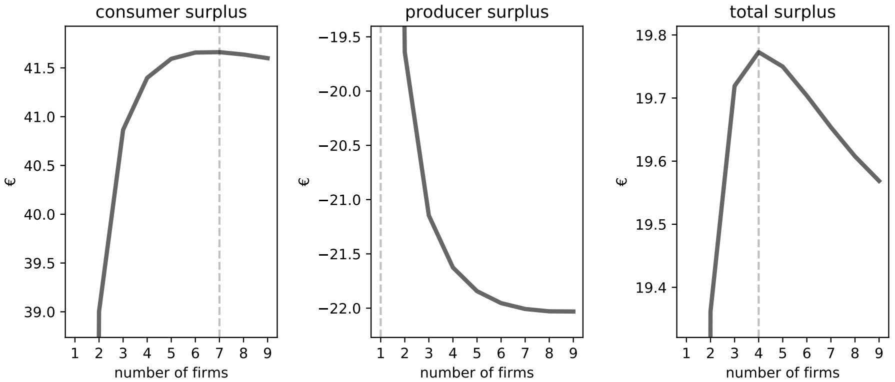
- We compute equilibria with n symmetric firms, varying n
- Two products per firm, data limits fixed at 1 GB and 10 GB
- Firms compete in (both) prices and base station density
- Solve for symmetric equilibrium
- Total spectrum B_0 is fixed: each firm gets B_0/n endowment

Varying Number of Firms: Equilibrium Outcomes



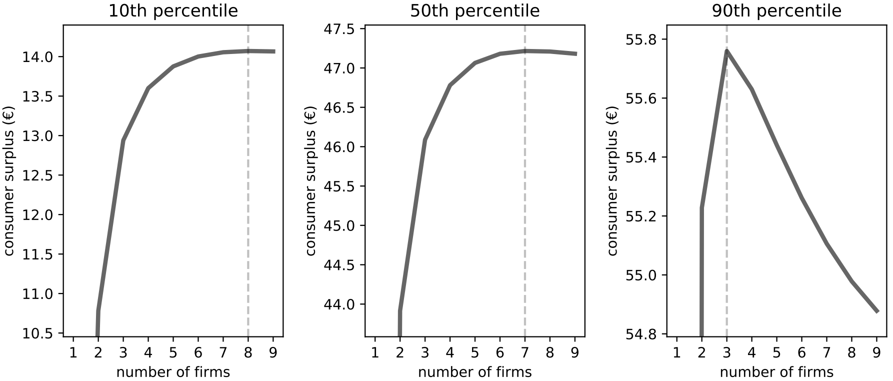
More on elasticities

Varying Number of Firms: Welfare



Welfare levels are relative to monopoly case

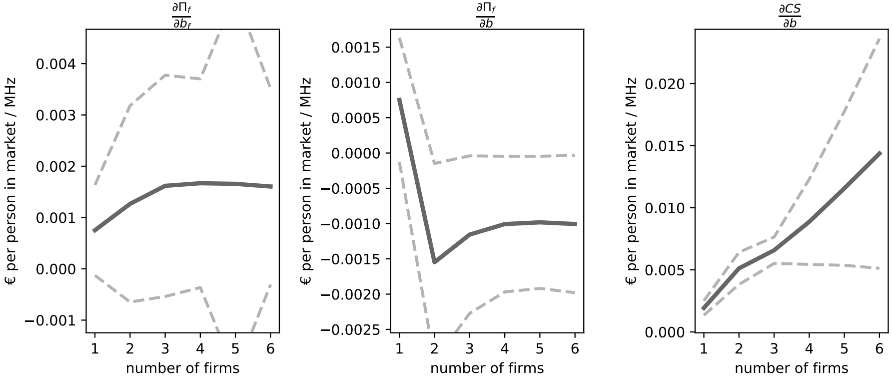
Varying Number of Firms: Distributional Impact



Marginal Value of Spectrum

- Re-compute previous equilibria adding slightly more bandwidth to the industry:
  - distributing it equally among all firms
  - distributing it to just one firm

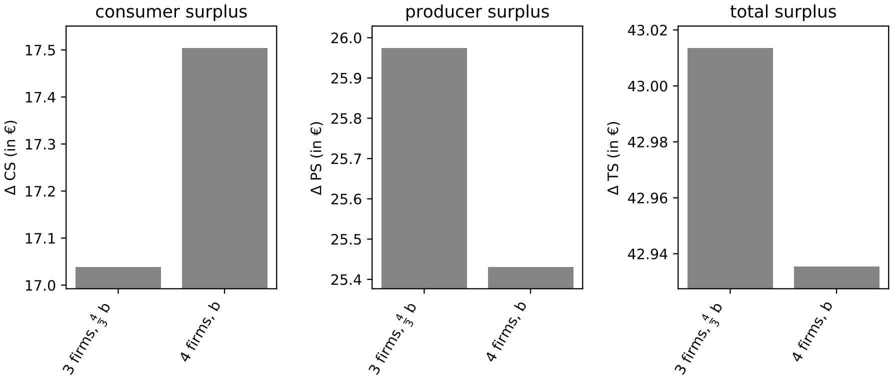
Marginal Value of Spectrum



Another Firm or More Bandwidth per Firm?

- In 2011, France allowed the entry of a 4th Mobile Network Operator, Free Mobile, with a generous spectrum allocation contract
- Compare two symmetric equilibria:
  - Three firms, each with bandwidth $\frac{4}{3}B_f$
  - Four firms, each with bandwidth B_f
- Compare each of these to previous equilibrium with 3 firms (firm endowment $B_f = B_0/3$)

Another Firm or More Bandwidth per Firm?



Endogenous Variables

Conclusion

- Assessed trade-off between economies of scale and market power using engineering-based model of infrastructure.
- (Some) consumers may benefit from fewer firms. Low-income consumers have a stronger preference for more firms.
  - Coordinated effects ignored in our analysis
- (Gross) social value of spectrum in mobile telecom much higher than firms' willingness to pay for spectrum.
- Allocating new spectrum to a new entrant is better for most consumers. Allocating it to incumbents is better for high-income consumers and total surplus.
- Code available on GitHub.

APPENDIX

Parameter Heterogeneity

$$\theta_i = [\theta_{pi}, \theta_x, \theta_{di}, \theta_v]' .$$

- Two heterogeneous parameters that will be allowed to vary by income:

$$\begin{pmatrix} \log(\theta_{pi}) \\ \log(\theta_{di}) \end{pmatrix} = \begin{pmatrix} \theta_{p0} \\ \theta_{d0} \end{pmatrix} + \begin{pmatrix} \theta_{pz} \\ \theta_{dz} \end{pmatrix} z_i,$$

where z_i is consumer's income

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Moments

Moments
$\mathbb{E}\left[e_m^O(\theta) - E\right] = 0$
$\mathbb{E}\left[\xi_{jm}(\theta) inc_m^{med}\right] = 0$
$\mathbb{E}\left[\bar{x}_{jm}(\theta) - \bar{x}_{jm}\right] = 0$
$\mathbb{E}\left[\left(\bar{x}_{jm}(\theta) - \bar{x}_{jm}\right) Q_{f(j)m}\right] = 0$
$\mathbb{E}\left[\left(\bar{x}_{jm}(\theta) - \bar{x}_{jm}\right) inc_m^{med}\right] = 0$
$\mathbb{E}\left[\xi_{jm}(\theta) v_j\right] = 0$
$\mathbb{E}\left[\xi_{jm}(\theta) popdens_m\right] = 0$
$\mathbb{E}\left[\xi_{jm}(\theta) dlim_j\right] = 0$

Noting that moments are computed over Orange products only

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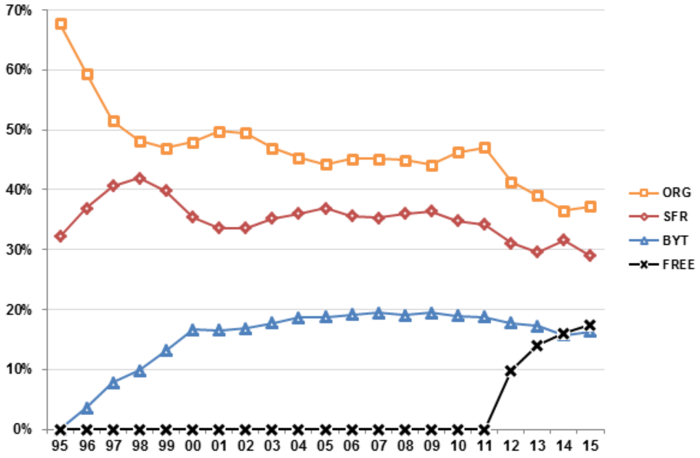
Evolution of Market Share



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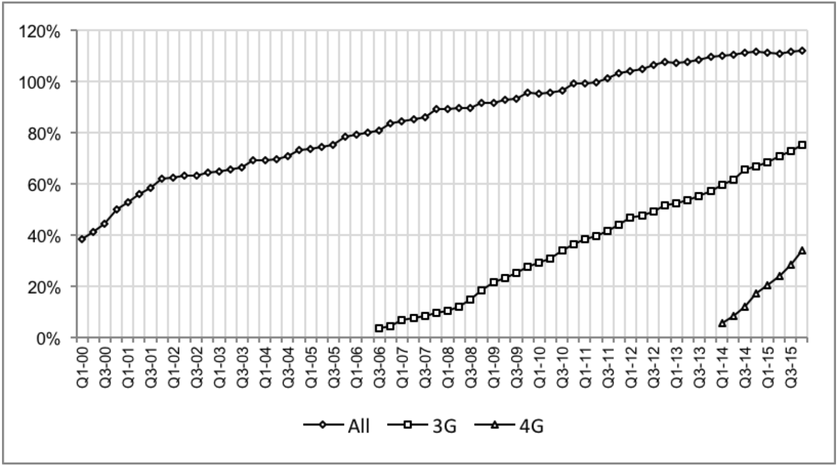
Penetration rate (ARCEP)



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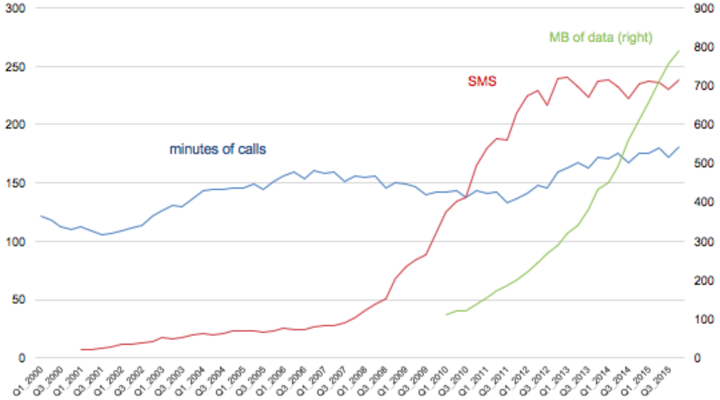
Mobile Services: Usage



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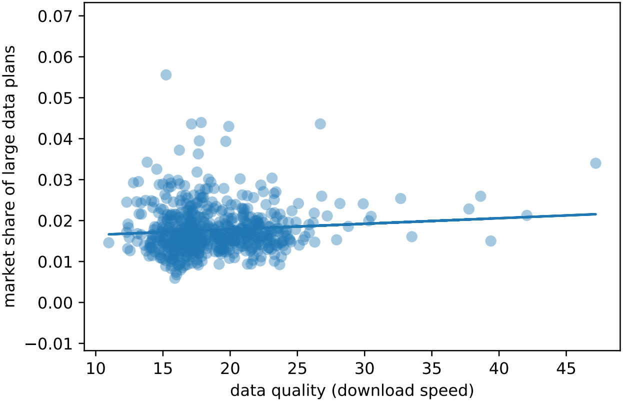
Qualities and Market Shares



*large data plans defined as those with a data limit ≥ 8000 MB

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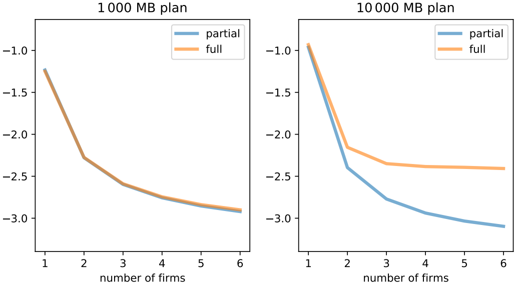
Full and Partial Elasticities



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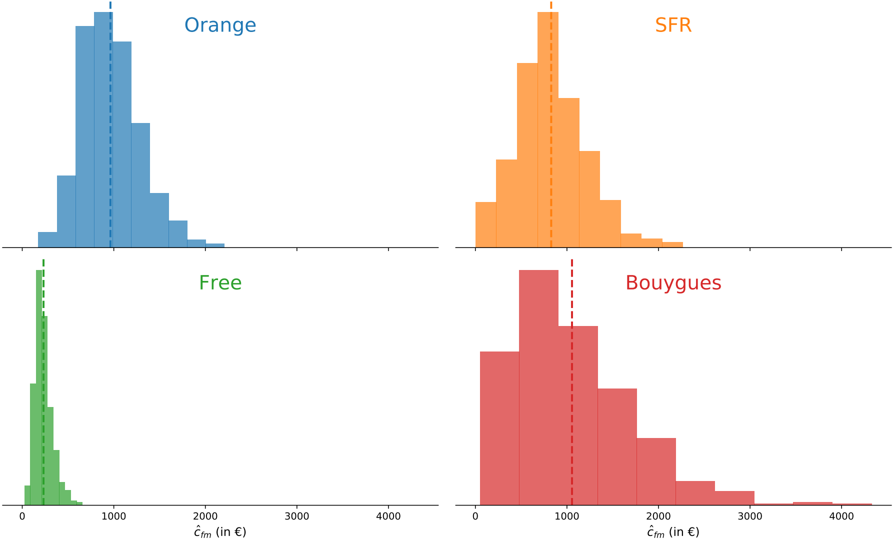
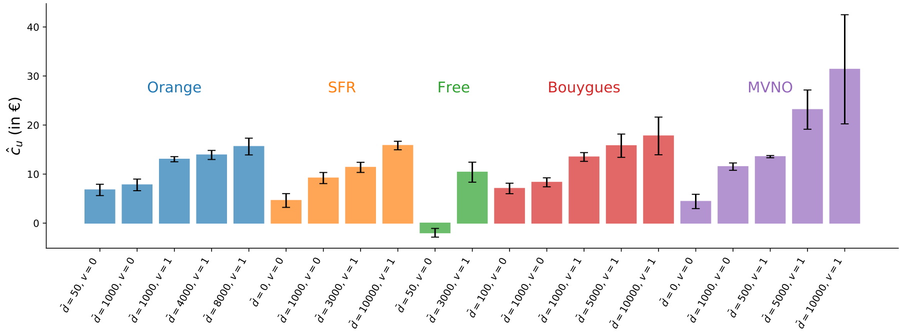
Estimated per-Base-Station Costs



Estimated per-User Costs



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Data Transmission

- Imagine we want to give the same download speed $\bar{Q}$ to all locations in a cell.
- Requires bandwidth $\frac{\bar{Q}}{q(r)}$ for user at distance r
- Integrating bandwidth needed across locations

$$B = G(R)^{-1} \int_0^R \frac{\bar{Q}}{q(r)} g(r)\, dr$$

- Rearranging,

$$\bar{Q} = \frac{B}{G(R)^{-1} \int_0^R \frac{g(r)}{q(r)} dr}$$

$\Rightarrow$ We need to take harmonic means when integrating over download speeds

Demand

- i indexes consumers, j indexes contracts, m indexes markets
  - x: choice of how much data to consume
  - $Q_{m,f(j)}$: download speed for firm f in market m
  - p_j: price
- A consumer's utility from a contract j in market m consuming x is

$$v\left(j, x, m; \theta_i, \zeta_i, \varepsilon_i\right) \equiv \underbrace{u\left(j, x, Q_{m,f(j)}; \theta_i, \zeta_i\right)}_{\substack{\text{utility from consumption} \\ \text{of mobile services}}} - \theta_{pi} p_j + \xi_{jm} + \varepsilon_{ij}$$

  - θ_i: parameter describing distribution of preference ▸▸ Heterogeneity
  - ζ_i: random preference parameter describing i's valuation of time spent downloading

◂ Go back

Discrete-Continuous Choice

$$v\left(j, x, m; \theta_i, \zeta_i, \varepsilon_i\right) \equiv u\left(j, x, Q_{m,f(j)}; \theta_i, \zeta_i\right) - \theta_{pi} p_j + \xi_{jm} + \varepsilon_{ij}$$

- ζ_i random variable realized after choice of j but before choice of x

$$\zeta_i \sim \mathit{Exponential}\left(\theta_{di}\right)$$

- Choice of how much data to consume:

$$x_m^*\left(j; \theta_i, \zeta_i\right) = \arg\max_{x}\left\{u\left(j, x, Q_{m,f(j)}; \theta_i, \zeta_i\right)\right\}$$

- Choice of contract:

$$j_m^*\left(\theta_i\right) = \arg\max_{j \in \mathcal{J}}\left\{\mathbb{E}\left[v\left(j, x_m^*(j; \theta_i, \zeta_i), m; \theta_i, \zeta_i, \varepsilon_{ij}\right)\right]\right\}$$

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Data Demand I

- We construct a model of utility from data consumption that yields finite consumption even with unlimited data access.

$$u\left(j, x, Q_{m,f(j)}; \theta_i, \zeta_i\right) = \zeta_i \log\left(1 + x\right) - \theta_c c_j\left(x, Q\right) + \theta_v v_j$$

  - v_j: dummy for unlimited voice
  - $c_j(\cdot)$: opportunity cost of time spent downloading

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Data Demand II

$$u\left(j, x, Q_{m,f(j)}; \theta_i, \zeta_i\right) = \zeta_i \log\left(1 + x\right) - \theta_c c_j\left(x, Q\right) + \theta_v v_j$$

- Institutional detail: contracts come with data limits, but they are soft. When limit is exceeded, download speed is heavily throttled.

$$c_j\left(x, Q\right) = \begin{cases} \frac{x}{Q} & \text{if } x \leq \bar{x}_j \\ \frac{\bar{x}_j}{Q} + \frac{\bar{x}_j - x}{Q^L} & \text{if } x > \bar{x}_j, \end{cases}$$

- Given parameters, we can predict how much a consumer will consume over the course of the month and how much utility they will derive from it.

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Scale Efficiencies

- Merger of two symmetric firms can yield higher quality at the same cost (scale efficiencies), holding data demanded constant
- **Economies of density**: Merged firm has a higher effective density of consumers
  - Data requests completed more efficiently the closer one is to the base station
  - On average, consumers and base stations are closer together, yielding higher download speeds
- **Economies of pooling**: Merged firm has twice the bandwidth
  - When we increase bandwidth (or channel capacity) and usage proportionately, download speeds increase
  - "The Pooling Principle" in operations literature
  - Carlton (1978): "there are economies of scale in servicing a stochastic market"

Summary Stats

	Mean	Std. Dev.	Min.	Max.
Customer data (Orange)				
Market Average Usage (MB)	1 043	194	554	1701
Fraction Users above Data Limit	0.18	0.03	0.10	0.28
Num. customers		4 425 831		
Quality and market data				
Quality Orange (Mbps)	33.02	11.35	3.97	89.87
Quality Bouygues (Mbps)	23.73	9.69	0.60	72.97
Quality Free (Mbps)	23.21	11.08	1.56	57.26
Quality SFR (Mbps)	17.60	8.60	0.39	52.30
Quality MVNO (Mbps)	24.79	7.12	5.13	49.06
Median income (Euros)	13 035	3 179	5 152	31 320
Number of markets		589		
Tariff data				
Price	23.47	14.57	2.00	64.99
Price (Orange)	23.92	11.06	12.07	38.74
Price (Others)	23.33	15.83	2.00	64.99
Data limit	3 081	3 570	0	10 000
Num. products		21		

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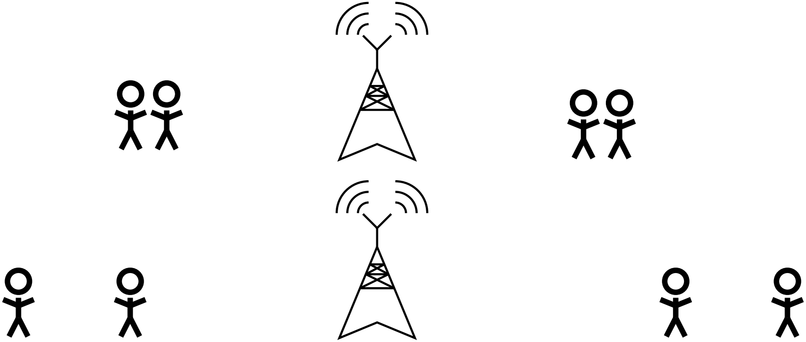
Urban vs. Rural



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Information Theory

- $q(r)$ – theoretical maximum download speed, distance r from antennae, with one unit of bandwidth
- Shannon-Hartley theorem gives maximum rate of data transmission:

$$q(r) = B \log_2 (1 + SINR(r))$$

where $SINR(r)$ is the signal-to-noise-and-interference ratio, and B is the bandwidth used

$$SINR(r) = \frac{S(r)}{N + I(R)}$$

Path Loss

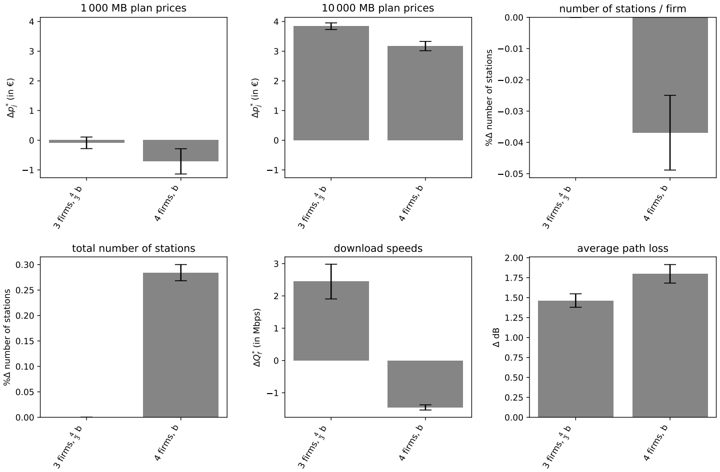
- Signal power declines with distance. In a vacuum, it would be proportional to the inverse square of distance traveled.
- We use the Hata model of path loss (assuming 30m transmission height, 1900 Mhz frequencies). Effective path loss exponent is ≈ -3.5
- Signal power at base station is regulated. We assume all base stations transmit effective isotropic power of 61 dBm.
- Taking harmonic mean over a base station's cell, average download speed (**channel capacity**) is:

$$\bar{Q} = \frac{B}{G(R)^{-1} \int_0^R \frac{g(r)}{q(r)} dr}$$

where g and G) reflect the cell's geometry. e.g., $g(r) = 2\pi r$ and $G(r) = \pi r^2$ for circular cell. (We use hexagonal cells.)

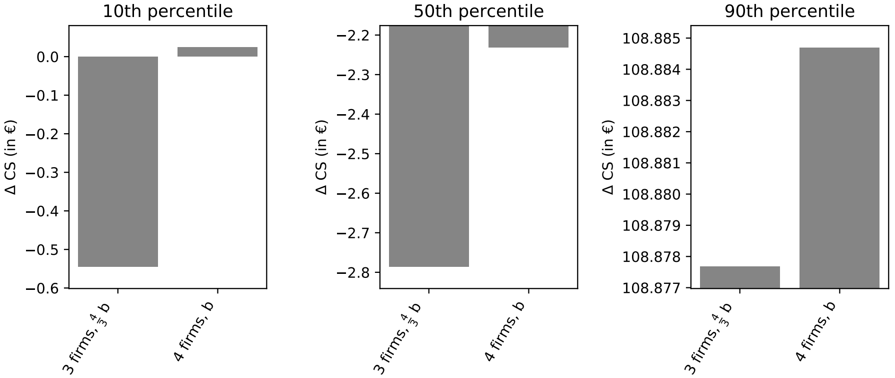
We also account for endogenous interference: we assume an omnidirectional signal with 30% signal power from the six adjacent base stations. Go Back

Another Firm or More Bandwidth per Firm?

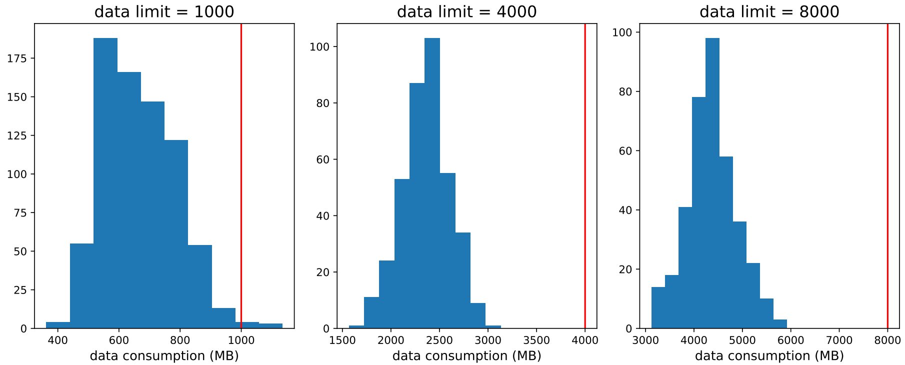


◂ Go Back

Another Firm or More Bandwidth per Firm?



Data Consumption



When consumer hits their data limit, in most cases their download speeds get throttled (with no impact on their bill)