The Adoption of Network Goods: Evidence from The Spread of Mobile Phones in Rwanda

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Motivation

- Network effects can generate inefficiency
  - Customers do not internalize the benefits from their adoptions to the rest of the network
  - Providers do not internalize the benefits from costly provision to social welfare
- Difficulty of measuring network effects:
  - Indistinguishable motivation: mimic others out of network benefit or similar taste?
  - High cost in gathering individual data in a network
- Two problems addressed in this paper:
  - How to capture the spillover benefits associated with network effects
  - How to evaluate the impact of policies

Context

- Rwanda
  - Demography
    - Low income $\rightarrow$ low demand
    - Very hilly $\rightarrow$ blocking signal propagation
    - High population density $\rightarrow$ more subscribers per tower
  - Mobile phone industry
    - Restricted entry
    - Few alternatives for remote communication
- Network rollout
  - Providers: monopolists (1998) $\rightarrow$ competitors (2005)
  - Coverage: urban centers (60% 2005) $\rightarrow$ broader area (95% 2009)

    Result from a combination of competitive threat and regulation
  - Prices (handset and network access):
    - high ($0.27 per call 2005) $\rightarrow$ low ($0.01- per second 2008);
    - changing price structures (no non-marginal charges 2008)

    Following global trend and government subsidy

Data

- Call detail records (CDRs): 4.5 years (01/2005-05/2009)
  - Anonymous identifiers for sender and receiver
  - Date, time, and duration
  - Cell towers used at the start and end of the transaction
  - Incurred charge
- Cell tower locations:
  - Infer missing data by a weighted sum of the coordinates of known towers (Appendix C)
- Individual locations:
  - Inferred from the sequence of cell towers used in one's call, using "important places" algorithm (Appendix D)
- Coverage maps:
  - Depict the raw coverage based on the location of towers, then average them to get individual coverage (Appendix A)
- Handset prices: weighted average of all handsets (Appendix E)
- Operator billing policies: operator's web site, reports from the government regulator, and news articles
- Household surveys:
  - EICV (2005-2010), Research ICT Africa's 2007 survey

Implicit Assumptions

- Calls reveal a social network
  - Accounts = individuals (disincentive to switch phone numbers)
  - A call reveals a desire to communicate (most calls are social)
    - conditional on individual's geographic locations
    - conditional on phone ownership
    - underweight option value for unrealized calls (e.g. emergency calls)
    - directed network (the calling party pays)
- Independence in links (immature market)
  - Call volume along a given link keeps constant as more contacts join the network
- Adoption as a dynamic decision (exogenous (high) handset price)
- Other simplifications
  - Ignore the other operator
  - Ignore SMS and missed calls
  - Ignore handset sharing

Model-Notations

- G: social network (directed graph)
- $G_i \subset G$: individual i's contacts (fixed)
- S_t: nodes subscribing in month t

Model-Calling Decision

i maximizes her utility from calling j

$$u_{ijt} = \max_{d \geq 0} v_{ij}(d, \epsilon_{ijt}) - c_{ijt} d$$

- d: calling duration from i to j in month t (integers)
- ϵ_{ijt}: utility shock; $\epsilon_{ijt} \overset{iid}{\sim} F_{ij}$
- v_{ij}: benefit of calls; $v_{ij}(d, \epsilon) = d - \frac{1}{\epsilon}[\frac{d^\gamma}{\gamma} + \alpha d]$
  - $\gamma > 1$: how quickly marginal returns decline
  - α: affects the censoring fraction of no call months dependent on cost
- c_{ijt}: cost $c_{ijt} = \beta_{call} p_t + h(\phi_{it}, \phi_{jt})$
  - β_{call} call price sensitivity
  - $\phi_{it} \in [0, 1]$: fraction of the area surrounding i receiving cellular coverage
  - $h(\phi_{it}, \phi_{jt})$: hassle cost given the caller and receiver's level of coverage
    $h(\phi_{it}, \phi_{jt}) =$
    $\beta_{coverage.from} \phi_{it} + \beta_{coverage.to} \phi_{jt} + \beta_{coverage.interaction} \phi_{it} \phi_{jt}$

Model-Calling Decision

- Optimal conditions

$$d(\epsilon, p_t, \phi_{it}, \phi_{jt}) = \begin{cases} [\epsilon(1 - \beta_{call} p_t - h(\phi_{it}, \phi_{jt})) - \alpha]^{\frac{1}{\gamma-1}} & \epsilon_{ijt} > \underline{\epsilon}_{ijt} \\ 0 & \epsilon_{ijt} \leq \underline{\epsilon}_{ijt} \end{cases}$$

$\underline{\epsilon}_{ijt} = \frac{\alpha}{1-\beta_{call} p_t - h(\phi_{it}, \phi_{jt})}$

- Expected utility

$Eu_{ijt}(p_t, \phi_t) =$
$\int_{\underline{\epsilon}_{ijt}}^{\infty} \left[d(\epsilon, p_t, \phi_t)(1 - \beta_{call} p_t - h(\phi_{it}, \phi_{jt}) - \frac{\alpha}{\epsilon}) - \frac{1}{\epsilon} \frac{d(\epsilon, p_t, \phi_t)}{\gamma} \right] dF_{ij}(\epsilon)$

Model-Adoption Decision

When i is not on the network, $u_{it} = 0$
When i is on the network

$$u_{it} = \sum_{j \in G_i \cap S_t} Eu_{ijt}(p_t, \phi_t) + wEu_{jit}(p_t, \phi_t) + \eta_i$$

- $w \in \{0, 1\}$: whether i value incoming calls
- η_i: an idiosyncratic benefit from being on the network; known by i but not observed by the econometrician; $E\eta_i = 0$

If i adopt at time τ

$$U_i^\tau = \sum_{t=\tau}^{\infty} \delta^t Eu_{it}(p_t, \phi_t) - \delta^\tau \beta^{handset} p_\tau^{handset}$$

- $\beta^{handset}$: price sensitivity

Estimation-Identification

- Observations: p_t (price per minute), $p_{\tau}^{handset}$ (price of handset), τ_i (adoption month), ϕ_{it} (coverage), communication graph (there is a link from i to j if i calls j at least twice)
- Instruments to identify adoption model: slope, incidental coverage (based on the interaction of electric grid and geographic features), fraction of contacts receiving subsidized handsets (Appendix B)

Estimation-Calling Decision

- Specify F_{ij} (the distribution of ϵ_{ijt}):
  In $N(\mu_{ij}, \sigma_i^2)$ with probability $1 - q_i$; $-\infty$ with probability q_i
- Deriving ϵ_{ijt} from data

$$\epsilon(d|p_t, \phi_{it}, \phi_{jt}) = \frac{d^{\gamma-1} + \alpha}{1 - \beta_{call} p_t - h(\phi_{it}, \phi_{jt})}$$

- Deriving likelihood functions

$$\begin{cases} F_{ij}[\epsilon(1|p_t, \phi_{it}, \phi_{jt})] & d_{ijt} = 0 \\ F_{ij}[\epsilon(d+1|p_t, \phi_{it}, \phi_{jt})] - F_{ij}[\epsilon(d|p_t, \phi_{it}, \phi_{jt})] & d_{ijt} = d > 0 \end{cases}$$

- Estimating parameters:
  - Common parameters: γ, α, β_{call}, $\beta_{coverage.from}$, $\beta_{coverage.to}$, and $\beta_{coverage.interaction}$
  - Distribution parameters: μ_{ij}, q_i, and σ_i

  Estimate common parameters and distribution parameters for a random subset $\rightarrow$ Estimate distribution parameters for the rest, imposing the estimated common parameters $\rightarrow$ Calculate expected duration and expected utility

Estimation-Adoption Decision

- Perfect foresight and independent decisions:

$$U_i^{\tau_i} \geq U_i^{\tau_i \pm K} \Rightarrow$$

$$\sum_{k=0}^{K-1} \delta^k u_{i\tau_i+k}(p_{\tau_i+k}, \phi_{\tau_i+k}) \geq \beta^{handset}(p_{\tau_i}^{handset} - \delta^K p_{\tau_i+K}^{handset})$$

$$\sum_{k=1}^{K} \delta^{K-k} u_{i\tau_i-k}(p_{\tau_i-k}, \phi_{\tau_i-k}) \leq \beta^{handset}(p_{\tau_i-K}^{handset} - \delta^K p_{\tau_i}^{handset})$$

- Perfect foresight and dependent decisions: narrower bounds
- Imperfect foresight with error of zero mean across individuals $\rightarrow$ moment inequalities

$$E\left[Z_{mi}(U_i^{\tau} - U_i^{\tau \pm K})\right] \geq 0$$

  for a set of instrument Z: $E[\eta_i|Z_i] = 0$, including $Z_{0i} = 1$
- Estimation

  Set $K = 2$(months), $\delta = 0.9^{1/12}$. Estimate $\beta^{handset}$

Estimation-Results

Calling Decision

Unified Parameters	Standard Error
γ	0.0006
α	0.3292
β_{call}	0.0001
$\beta_{coverage.from}$	0.0051
$\beta_{coverage.to}$	0.0053
$\beta_{coverage.interaction}$	0.0079

Communication Graph

	Quantile:	0.01	0.25	0.50	0.75	0.99
Links (124.6m)	μ_{ij}	1.60	3.52	4.40	5.14	7.32
	SE(μ_{ij})	0.12	0.30	0.39	0.51	1.64
	N per link	6	19	45	52	53

	Quantile:	0.01	0.25	0.50	0.75	0.99
Nodes (1.5m)	σ_i	0.13	0.49	0.67	0.95	2.01
	SE(σ_i)	0.01	0.02	0.04	0.06	0.28
	q_i	0.06	0.21	0.44	0.82	1.00
	SE(q_i)	0.00	0.01	0.02	0.04	0.39
	N per node	13	227	637	2,464	27,725
Overall	N per parameter	6	21	41	46	51
	$N_{observations}$	4 billion				

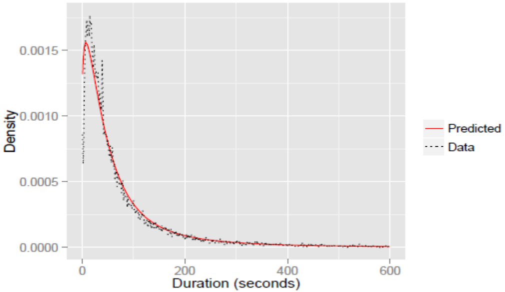
Adoption Decision

	Parameter	Estimate
Adoptions (1m)	$\beta^{handset}$	0.1379

Estimation-Results

- The value of joining a network
  - Call utility model (cost): adopt two months earlier: pay $0.9 more; two months later: pay $0.94 less
  - Adoption model (benefit): adopt two months earlier: gain $0.64 more; two months later: give up $0.87 Call utility model underestimate utility after adoption
- Model fit

FIGURE 4. Call Model Fit



Months without call:	Data	88.0%
	Predicted	88.2%

Computed on random subsample of 10,000 links.

Simulation-Method

- Equilibrium Γ: adoption times $\tau = [\tau_i]_{i \in S}$ satisfying
  - $\tau_i = 0$ for $i \in S_0 \subset S$
  - $\tau_i = argmax_t U_i^t(\eta_i, \tau_{-i})$ for $i \in S \backslash S_0$
- Simulation procedure (given η):
  - Propose a candidate adoption path τ^0
    For baseline use the observed adoption path
  - $\tau_i^{k+1} = argmax_t U_i^t(\eta_i, \tau_{-i}^k)$
  - Stop when $\tau_i^{k+1} = \tau_i^k$ for all i
- Generate η_i
  - Cannot generate from distribution of η since demand is interlinked (why?)
  - Use $U_i^{\tau_i} \geq U_i^{\tau_i \pm K} \Rightarrow$ to determine lower bound and upper bound (see p26 for a closed form expression)
  - Compute upper and lower bound for the set of equilibria $[\underline{\tau}_i, \bar{\tau}_i]$ and best guess by setting $\eta_i = \frac{\underline{\eta}_i + \bar{\eta}_i}{2}$

Simulation-Revenue and Utility

- Revenue

$$R^{\Gamma} = \sum_{i \in S} \sum_{t \geq \tau_i} \delta^t p_t \sum_{j \in G_i \cap S_t} Ed_{ijt}(p_t, \phi_{it}, \phi_{jt})$$

- Total Utility (less calling and coverage costs, but include handsets cost)

$$U^{\Gamma}_{calls} = \sum_{i \in S} \sum_{t \geq \tau_i} \delta^t \sum_{j \in G_i \cap S_t} Eu_{ijt}(p_t, \phi_{it}, \phi_{jt}) + wEu_{jit}(p_t, \phi_{it}, \phi_{jt})$$

- Handsets cost

$$C^{\Gamma}_{handsets} = \sum_{i \in S} \left[\delta^{\tau_i} p^{handset}_{i\tau_i} - \delta^{\bar{T}^{data}} p^{handset}_{i\bar{T}^{data}} \right]$$

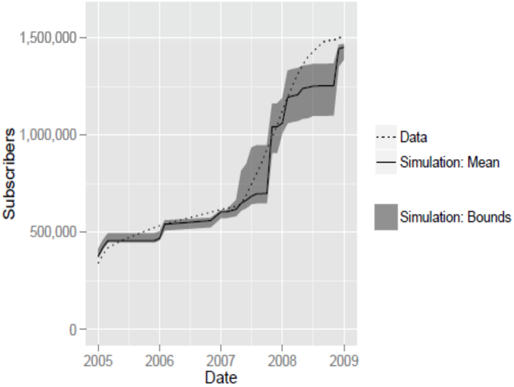
- Net utility

$$U^{\Gamma}_{net} = \frac{1}{\beta^{handset}} U^{\Gamma}_{calls} - C^{\Gamma}_{handsets}$$

  - Note: $R^{\Gamma(\underline{\eta})} \leq R \leq R^{\Gamma(\bar{\eta})}$ and $U^{\Gamma(\underline{\eta})}_{calls} \leq U_{calls} \leq U^{\Gamma(\bar{\eta})}_{calls}$. But this is not true for U^{Γ}_{net} (omit η)

Simulation-Results

FIGURE 5. Simulation Fit



Fit metrics	Adoption month in data vs. adoption month under Lower equilibrium	Mean	Upper equilibrium
Correlation	0.86	0.87	0.83
Mean deviation	5.80	2.82	-0.83
Mean absolute deviation	6.63	4.56	5.08
Median deviation	5	2	-2
Median absolute deviation	5	3	4

Simulation-Results

- Estimated revenue: \$205-235m (Compare with \$302m in data)
- Estimated utility from calls: \$75-91m (\$3-4 per subscriber per month, or 1-2.4% of household consumption)
- Estimated cost of handsets: \$21-26m (\$1 per subscriber per month, or 0.3-0.6% of household consumption)
- Estimated net utility: \$54-65m (\$2-3 per subscriber per month, or 0.6-1.8% of household consumption)

Simulation-Robustness

- Coordinated adoption: narrower bounds
- Handset sharing: sharing costs and call shock distributions are independent in this model
- Utility from incoming calls: $w = 0$ in the model; for $w = 1$ results are similar
- Homophily: not a problem here

Application-Targeting Adoption Subsidies

Analyzing the effect of the 2008 adoption subsidy program

- Describe effects of Subsidized Handsets
    - Discounted handsets of identifiable models are distributed to rural districts
    - In districts level: Allocating additional 1% handsets generates more than 1% increasing in adoption → network effects (Table 7)
    - District spillover: Many handsets were activated in urban areas
    - Usage (duration): recipients' network structure is similar to others who subscribed around the same time → recipients value the subsidies

Application-Targeting Adoption Subsidies

- Simulated impact of Adoption Subsidy
  - Assumptions:
    - Subsidy recipients represent the full set of eligible individuals
    - Recipients did not delay adoption in order to receive a subsidy
    - Recipients preferred taking the subsidy at the point of adoption to purchasing any time in the following 4 years
  - Simulations:
    - Baseline
    - No subsidy and only recipients change their behavior
    - No subsidy and all individuals adjust
  - Results (Table 9):
    - The subsidy improved welfare
    - The operator might have the incentive to subsidize
    - Most of the effect is a proximal effect
    - The subsidy provides substantial benefits to the contacts of recipients
  - Predict mobile internet adoption based on data of mobile phone (Appendix K)

Application-The Provision of Service to Rural Areas

Analyze the effect of regulations on rural expansion (10 rural towers earning the lowest monthly revenue)

- Simulation
  - Baseline
  - No expansion and only immediate effect on call utilities
  - No expansion and full impact including the effect on adoption
  - When consider the population density: $\Delta \tilde{R}^{\Gamma} = \lambda \Delta R^{\Gamma} - C$, $\Delta \tilde{U}^{\Gamma}_{net} = \lambda \Delta U^{\Gamma}_{net}$
- Results (Table 10)
  - Rural expansion improved welfare, but to a small extent (0.5%)
  - Private benefits were too dispersed for rollout in the absence of intervention
    - The rollout was unprofitable for the operator (??)
    - The benefits were too low and dispersed for consumers to finance tower construction themselves
  - Expansions profit both customers and operators for high population densities ($\lambda > 1.43$) and are unprofitable for both parties for low population densities ($\lambda < 0.66$). Expanding the network is socially optimal but not profitable for operators when $0.72 < \lambda < 1.26$

Conclusion

- Introduce a new method to estimate and simulate the adoption of network goods
- Customers do not internalize the benefits from their adoptions to the rest of the network $\rightarrow$ subsidize adoption and target neighbors besides individual nodes
- Providers do not internalize the benefits from costly provision to social welfare $\rightarrow$ regulate coverage for a country with moderate population density

Discussion

- Problems for a mature market
  - Is it reasonable to omit individual choice over handsets?
  - Are individual utility arising only from communication?
  - How to address the problem of homophily?
- Model the operator's behavior
  - How does the operator expand the network (construction of towers, introducing handset models, etc.) to maximize its profit, given users strategies?
  - What is the optimal pricing structure for the operator and for the whole society?
  - How do the users adjust their behavior according to the operator's choice?