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COMPETITION IN NETWORK INDUSTRIES: EVIDENCE FROM THE RWANDAN MOBILE PHONE NETWORK

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Abstract: This paper analyzes the potential for competition policy to affect welfare and investment in a network industry. When a network is split between competitors, each internalizes less network effects, but may still invest to steal customers. I structurally estimate the utility of adopting a mobile phone from subsequent usage, using transac-tion data from nearly the entire Rwandan network. I simulate the equilibrium choices of consumers and network operators. Adding a competitor earlier could have reduced prices and increased incentives to invest in rural towers, increasing welfare by the equivalent of 1% of GDP.

JEL Classification Codes: O33, L96, O180, L51
Keywords: network goods, infrastructure, information technology

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1. Introduction

How should societies manage dominant networks? Governments commonly intervene to spur competition, in the hope that consumer choice will discipline firms. However, competition also splits consumers across networks. As a result, firms internalize less network effects; that could lower incentives to invest unless it is offset by a sufficient motive to steal customers from competitors.

Despite extensive theory, there is little empirical work to guide policy for classical network goods, whose users value links with other users (such as communications, payment, or social networks).[1] This paper focuses on emerging economies, where telecom networks have begun to play an outsized role. Although voice calls still account for the majority of revenues, in these societies mobile phone operators are emerging as gatekeepers to information services, the internet, and, increasingly, financial transactions.[2] The details of how to manage competition have been 'a main bottleneck' to the development of the sector (World Bank, 2004), and regulators have little guidance on when to tilt favor, allow consolidation (Moody's, 2015), or split firms (Reuters, 2017).

This paper evaluates the effects of competition on investment and welfare in Rwanda's mobile phone network, using 5.3 billion transaction records from an incumbent operator that held over 88% of the market. I extend the network demand system of Björkegren (2019) to allow for competition, and model a tractable supply side to compute equilibria between firms and 1.5 million networked consumers. I evaluate how introducing competition earlier could affect prices, investment, and welfare. I find

[1] See Katz and Shapiro (1994) and Farrell and Klemperer (2007) for review articles. The theory on competition in developed country landline networks (Armstrong, 1998; Laffont et al., 1998; Laffont and Tirole, 2001) can be inconclusive (Vogelsang, 2013), and with few exceptions (e.g., Valletti and Cambini, 2005) omits factors important for growing networks such as investment and network effects in adoption.

[2] Voice accounts for 60% of the my telecom partner's parent's African revenue in 2017 (including two small operations outside of Africa).

that adding a competitor could have increased incentives to invest, and increased welfare by the equivalent of 1% of GDP. This paper represents the first empirical analysis of competing classical network goods using micro data.

Like most African countries, Rwanda initially licensed a monopoly mobile phone operator and gradually allowed entry (Williams et al., 2011). Each firm was required to interoperate so consumers could call customers of other networks, but each offered coverage exclusively to its own customers. I study a period during which the regulator allowed entry of a second firm, which ended up being poorly run and never captured much market share. Despite this entrant's weaknesses, within 4.5 years the incumbent lowered real calling prices by 76% and nearly quadrupled the number of towers, increasing coverage from 60% to a nearly complete 95% of land area. My data from the incumbent cover nearly the entire network of mobile phones at the time, and nearly every call over those 4.5 years.

Immediately after this period, the regulator granted an additional license to a well managed competitor, which built coverage in lucrative urban markets, charged lower prices, and captured market share. Could the government have done better by granting this additional competitor a license at the beginning of the period?

I answer these questions using an empirical approach that proceeds in three steps.

First, the government chooses whether to grant a license to an additional competitor, and if so, the interconnection rate that each firm pays the other when its subscribers call in to their network.

Second, firms choose from a menu of strategies. The entrant builds urban towers and selects a path of calling prices, anticipating the choices of the incumbent. Then, the incumbent selects calling prices and whether to build the nearly complete set of towers it actually built, or scale back low population rural towers. I use engineering cost data collected under mandate by the regulator. I require that firms charge the same rate for on- and off-network calls, proportional to the incumbent's baseline price path. Because these terms could have been implemented by the regulator, my results represent a lower bound of the potential welfare benefits of competition under more flexible policies.

Third, I model the utility of adopting and using a phone. Almost all phones in Rwanda were basic, prepaid mobile phones.[3] I infer the value of each voice connection from subsequent interaction across that connection, using the method and estimates of Björkegren (2019). This approach bypasses most of the simultaneity issues that result from inferring the value of links from correlations in adoption.[4] Calls are billed by the second, so a subscriber must value a connection at least as much as the cost of calls placed across it.[5] Variation in prices and coverage identifies the underlying demand curve for communication across each link. Consumers are forward looking, choosing when to adopt by weighing the increasing stream of utility from communicating with the network against the declining cost of handsets. I extend Björkegren (2019) to allow consumers to select and switch between operators. I survey Rwandan consumers to estimate switching costs and idiosyncratic preferences with hypothetical questions.

Equilibria are computed using an iterated best response algorithm. Firms commit to price and rollout plans, then consumers publicly announce adoption dates, operator choices, and usage. I index the multiple equilibria in demand by exploiting supermodularity (similar to Jia (2008) and Björkegren (2019)); firms anticipate the index of the equilibrium that consumers will play.

In resulting equilibria, building a tower increases the adoption and usage of individuals who call from that location, which increases the adoption of those they are connected to, which increases the adoption of others with no connections to that location, and so on. A monopolist will internalize these demand spillovers within the

[3]In the period I study mobile money did not exist. As of this writing, only 9% of mobile phones in Rwanda are smartphones (ResearchICTAfrica, 2017).

[4]One individual may adopt after a contact adopts because the contact provides network benefits, or because connected individuals share similar traits or are exposed to similar environments.

[5]In the first 14 months of the data, calls are billed by the first minute and every following 30 seconds.

entire network. Under competition, interoperability causes benefits to spill over into competing networks, but each firm internalizes only spillovers within its own network.

I simulate the industry through December 2008, and find:

Adding a competitor could have lowered prices by 30-50% and *increased* incentives to invest in rural towers, under an interconnection rate of $0.11/minute. This policy would have increased the net welfare provided by the mobile phone system by up to 60%, an amount equivalent to 1% of GDP or 3-5% of the official development aid received by the country over this timespan. This suggests that the industrial organization of emerging networks can have profound welfare implications.

Competition affects incentives to invest in rural towers through three forces. Lower prices, and the splitting of the network lower the incremental revenue from investment. But firms also invest to attract consumers from the other operator. Network spillovers are relatively small here: the incumbent internalizes 88-93% of incremental revenue when the network is split (holding fixed operator choices). The business stealing effect dominates, accounting for 64-70% of the incremental revenue earned by the incumbent. It is large because many semiurban consumers partially value rural coverage. The net effect depends on policy: while the return on investment (ROI) can be higher under competition, it declines as the networks are made more compatible through lower interconnection fees.

If the incumbent or both firms jointly chose the terms of interconnection, under these terms they would have effectively blocked competition. This outcome is similar to previously unregulated Somalia, where it was not possible to call between competing mobile phone networks, and is reminiscent of many network industries that do not endogenously develop compatibility (Katz and Shapiro, 1985).

A policy to reduce switching costs (number portability) increases the level of competition. Delaying entry mutes its effects during this time period.

A limitation to my approach is that the network is illuminated by usage, so individuals who do not adopt under baseline conditions are omitted. I model the behavior of nodes in this 'dark' portion of the network, and report results for shorter time horizons before these nodes would have adopted.

Altogether, this paper introduces an approach that could be applied by a regulator planning scenarios to handle a dominant monopoly network. I combine data from a dominant network with models of firm and consumer behavior, to anticipate how the industry would evolve under competition. The key to this exercise is ensuring those models are realistic. Some of the information I use to discipline these models would be available to such a regulator: choices made under the incumbent, and data from markets that were competitive at the time. However, I also benefit from observing Rwanda after the market became competitive. Altogether, this approach can be used to evaluate the effect of a wide class of policies; in addition to what I consider here: breaking up the incumbent, requiring networks to interconnect under heterogeneous rates, directly regulating coverage or the price of calls, and changing taxes on handsets and airtime.

Related Literature. This paper builds on the classical network demand system estimated in Björkegren (2019), which has parallels to Ryan and Tucker (2012)'s model of videoconferencing adoption. Most empirical work on classical network goods simply measures the extent of network effects; see for example Saloner and Shepard (1995), Goolsbee and Klenow (2002), and Tucker (2008). Common demand system simplifications can provide misleading estimates in these industries. I find that revenue estimates can be biased ranging from 52% too small to 86% too large in demand systems that do not model the full structure of the network (by omitting interdependence in consumer decisions, modeling network benefits in aggregate, or treating links as random draws).

There is a much larger literature on goods with *indirect* network effects, for which consumers benefit from additional users not because they value links with those users, but because popular platforms are better served by sellers. These include platforms and video formats (Ohashi, 2003; Gowrisankaran et al., 2010). Lee (2013) considers software compatibility (exclusivity) arrangements in video game platforms using a dynamic model of demand that holds fixed prices and investments. In a natural experiment, Farronato et al. (2020) find that service and usage outcomes change little when two competing pet sitting platforms merge.

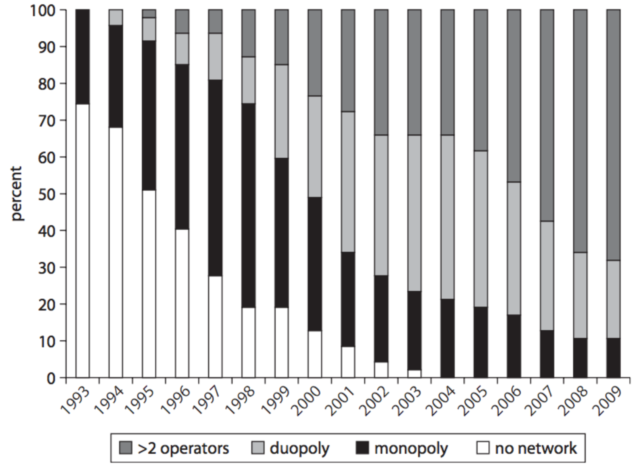
Much of the dynamic oligopoly literature focuses on settings with static demand (Ericson and Pakes, 1995). Gowrisankaran and Rysman (2012) model dynamic demand for durables, with firms that make per-period pricing decisions. I study dynamic provision of service for a durable that has a flow utility that changes depending on whether contacts have adopted, calling prices, and changing spatial coverage.[6] Since I can use regulator cost data, I skip estimating costs from dynamic decisions (Bajari et al., 2007; Pakes et al., 2008).

Goettler and Gordon (2011) and Igami (2017) together suggest the effect of competition on innovation can vary based on industry primitives. My setting differs in that operators face network effects, and earn revenue from ongoing service fees so do not compete with previous vintages of product.

My approach complements comparisons between countries that set different telecom policies. Faccio and Zingales (2017) and Genakos et al. (2018) find that increases in a telecom competition index are associated with price reductions, and Grajek and Röller (2012) find that a higher index of access to incumbents' infrastructure reduces investment in EU fixed line networks.[7]

[6]The model has both classical network effects in adoption (my utility depends on whether my particular contacts adopt) as well as indirect network effects in coverage (if more customers adopt, even if I have no desire to talk with them, my operator may find it more profitable to build towers).
[7]For reviews see Cambini and Jiang (2009) and Manganelli and Nicita (2020).

FIGURE 1. Mobile Telecom Competition in sub-Saharan Africa



Percent of countries with different industry structures. Source: Williams et al. (2011).

2. Context

Developing country phone systems. Developing country regulators typically started mobile phone industries by granting temporary monopolies, and then gradually licensed additional competitors (see Figure 1). Licenses commonly require firms to submit business plans, describing tower investments and pricing strategies (World Bank, 2013), and required networks to be interoperable so that users could call across networks, with explicit terms of interconnection.[8] (Left to the market, incumbents typically demand prohibitively high fees for interconnection; but even when network sizes are balanced, firms can use interconnection rates as an instrument of collusion (Armstrong, 1998; Laffont et al., 1998).) It is common for regulators to telegraph future policy by announcing entry dates or glide paths for interconnection, though there are occasional surprises. Later entrants typically charged lower prices and served densely populated areas, which are more lucrative.

[8]Licenses include rights to use specific bands of electromagnetic spectrum. Availability of spectrum was not a major constraint for regulators in poorer countries in this era, as there were few competing uses. See Supplemental Appendix S4.1.

Table 1. Mobile Telecommunications in sub-Saharan Africa

	Mean	SD
Number of operators	3.27	1.48
...top market share	0.58	0.19
...second highest market share	0.32	0.09
Market concentration (HHI)	0.49	0.21
Interconnection charges are regulated	97%	
...based on costs (LRIC or FDC)	71%	
...based on benchmarks	43%	

Industry statistics from 2015 or latest year available, source: regulator reports and news articles. Regulation statistics from 2015, for all SSA countries with available regulatory data (ranges from 21 to 41 countries depending on question), source: ITU.

However, there is little consensus on the optimal ground rules for competition. Table 1 shows that sub-Saharan Africa has a wide diversity in levels of competition, and how interconnection rates are set.[9]

Rwanda. In the aftermath of the genocide and civil war, the Rwandan government in 1998 granted a temporary exclusive license to a multinational operator to build and run a mobile phone system (Operator A). Rwanda's licenses allow an operator to set consumer prices at its discretion, but require specifying towers to be constructed over a 5 year horizon, updated upon renewal.[10] Most tower investments were driven by market incentives, but the operator was required to cover a handful of rural priority areas (amounting to 11% of rural towers active by 2009; Björkegren (2019)).

In 2003, the government announced it would provide a license to a second mobile operator, which entered in 2005 (Operator B). The second operator turned out to be poorly run and have quality issues. It was part of the former state landline company, but was purchased by an American satellite entrepreneur who was disconnected from

[9]Additionally, most interconnection models are designed for mature developed country networks, and so do not account for network effects in adoption.

[10]These are enforced: when Operator B failed to comply with its rollout plan, it was fined and its license was ultimately revoked.

realities on the ground (WSJ, 2006; IGIHE.com, 2011). After several changes in ownership, it reached a maximum of 20% market share for a brief period after the end of my data. In 2011, its license was revoked for failure to meet obligations.[11]

In 2008 the Rwandan regulator asked for bids and rollout plans for a third license. It granted a license to a third multinational operator (Operator C), which entered at the end of 2009, and renewed the previous operators' licenses. A consultant recommended lowering interconnection rates based on cost data (PwC, 2011).

In 2011, the assets and license of Operator B were absorbed into Operator D. In 2018, Operator C and D merged, bringing the market back to a duopoly.

See Figure 2 for the evolution of handset prices, accounts, calling prices, and coverage. This paper uses data from the period 2005-2009. Because the incumbent expected a firm to enter in 2005, starting conditions include dynamic effects of anticipating a new entrant. The calling price plot shows the baseline calling price, and foreshadows a counterfactual where Operator C is granted a license in 2005 at an interconnection rate of $0.11 per minute.

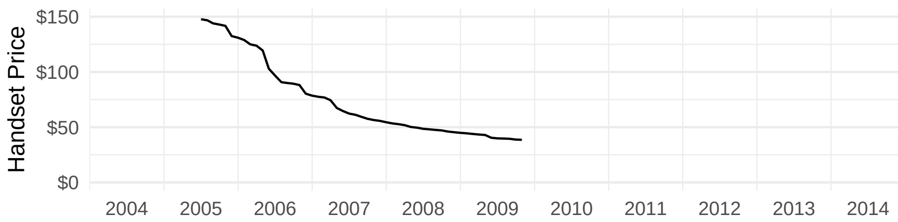
Consumer choice. Table 2 shows statistics on phone adoption and usage in Rwanda and several sub-Saharan African countries. Handsets are standard, imported models, with prices that track global trends. Most are purchased at retail price.[12] During this period, phones were used primarily for voice calls, and almost all phone plans are prepaid, with no monthly fee but a marginal charge per second. Mobile money did not exist at this point, and I do not explicitly model utility from text messages, missed

[11]WSJ (2006) reports that the operator "had no customer-service department and 12 employees whose sole job was to play on the company soccer team." The Registrar General, Louise Kanyonga said, "The company was mismanaged and their liabilities far outweigh their assets... This has been a real learning experience for our government. We need to ask how this happened."

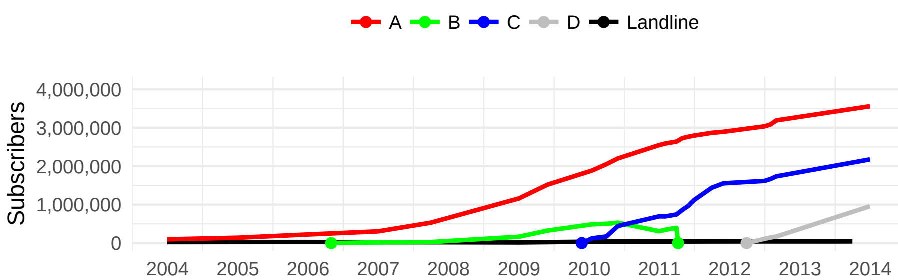
[12]In Rwanda most are purchased from independent sellers: operator handset sales records account for only 10% of total handsets activated during the period of my data.

FIGURE 2. Development of Telecommunications in Rwanda

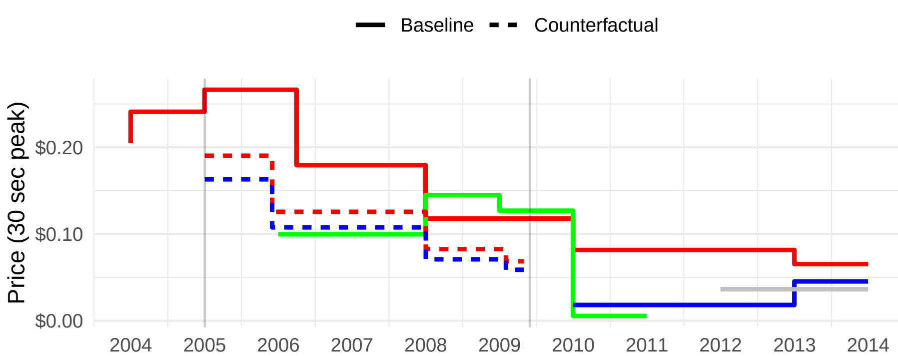
(a) Handset Price (real, quality adjusted index)



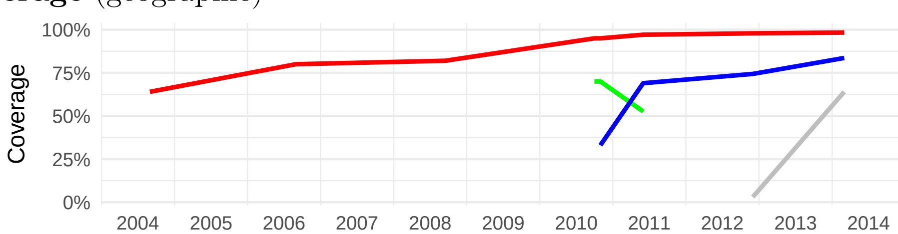
(b) Accounts



(c) Calling Price, On Network (30 second, nominal)



(d) Coverage (geographic)



Handset prices reported during the years I have data on prices and quantities. I report baseline calling prices and the prices from a counterfactual where Operator C enters in 2005 with an interconnection rate of $0.11 per minute. Sources: archived operator websites and regulator reports.

TABLE 2. Mobile Phone Usage among Owners in sub-Saharan Africa

	2007-8		2010-11	
	Rwanda	SSA**	Rwanda	SSA*
Received phone with a contract	0%	3%	3%	11%
Use phone for				
Voice calls	95%	98%	100%	99%
Music or radio	6%	14%	35%	46%
Taking photos or videos	5%	15%	24%	39%
Email	2%	3%	13%	14%
Sending or receiving money	-	-	18%	18%
Browsing Internet	-	-	15%	17%
Facebook or other social network	-	-	14%	16%
Apps (downloaded)	-	-	6%	15%

Source: RIA household surveys 2007-2008 and 2010-2011. *: Representative samples of mobile phone owners in Cameroon, Ethiopia, Ghana, Kenya, Mozambique, Namibia, Nigeria, Rwanda, South Africa, Tanzania, and Uganda; **: also Benin, Botswana, Burkina Faso, Cote d'Ivoire, Senegal, and Zambia. A dash indicates that question was not asked in that survey round.

calls, international calls, and calls from payphones.[13] Any value these omissions provide is captured in a residual in the adoption decision.

3. DATA

This project uses several data sources:[14]

Call detail records: As a side effect of providing service, mobile phone operators record data about each transaction, called Call Detail Records (CDRs). This project uses 4.5 years of anonymous call records from Operator A, which held above 88% of the market during this period. This data includes nearly every call between the operator's mobile phone subscribers, numbering approximately 400,000 in January 2005 and growing to 1.5 million in May 2009. It does not include the small number of calls to individuals who subscribed to Operator B. For each transaction, the data reports: anonymous identifiers for sender and receiver, corresponding to the phone

[13]See Supplemental Appendix S1 for more details.

[14]For more information see Supplemental Appendix S1-S3.

number and handset, time stamps, the location of the cell towers used, and call duration.[15] I aggregate durations to the monthly level.

Operator costs: The Rwandan regulator collects cost data from operators in order to ensure interconnection rates are 'derived from relevant costs' (RURA, 2009). I use long run incremental costs from a consultant study (PwC, 2011), and the cost of operating towers from a public study commissioned to set the regulated prices of infrastructure sharing (RURA, 2011).

Coverage: A rollout plan, $\mathbf{z} = \{(t_z, x_z, y_z)\}$, is defined by tower build dates and geographical coordinates. $\mathbf{z}_{(r)}$ represents the rollout that builds urban towers but only the proportion r of rural towers covering the highest populations, so that $\mathbf{z}_{(100\%)}$ represents the baseline rollout.[16] I create coverage maps by computing the areas within line of sight of the towers operational in each month, a method suggested by the operator's network engineer. Elevation maps are derived from satellite imagery recorded by NASA (Jarvis et al., 2008; Farr et al., 2007).

Individual locations and coverage: $\phi_{it}(\mathbf{z}) \in [0,1]$ represents the coverage available at individual i's most used locations under rollout plan $\mathbf{z}$, computed in Björkegren (2019) using a method analogous to triangulation.

Handset prices: I create a monthly handset price index $p_t^{handset}$ based on 160 popular models in Rwanda, adjusting for quality and weighting each model by the quantity activated on the network.

Consumer survey: To estimate the costs of switching, and idiosyncratic preferences for the entrant, I posed hypothetical incremental switching exercises to 89 mobile phone owners in Rwanda in the summer of 2017.

[15]Data are missing for May 2005, February 2009, and part of March 2009.
[16]Rankings determined based on population within a 10 km radius.

4. Model

The incumbent arrives in month $t = 0$ (January 2005) with an initial set of subscribers and towers. The government announces policy, each firm decides paths of calling prices and coverage, and each consumer decides which month to adopt a phone, with what operator, and how much to call each contact. I assess results under different time horizons $\tilde{T}$. I consider the handset market as perfectly competitive, with exogenous prices unaffected by the market for service.

4.1. **Government.** In month $t = 0$, the government announces its policy through $\tilde{T}$: either it will not license an additional competitor ('baseline'), or will additionally license Operator C ('competition') with interconnection fee f, a measure of compatibility. Counterfactuals will consider granting the license in $t = 0$, or after a delay so consumers can select the new operator starting in $t = 42$ (July 2008).

The government earns revenue from taxes on adoption ($\tau_{it}^{handset}$) and usage (τ_{it}^{usage}); these rates are held fixed and their path is announced in advance.[17] I do not take a stand on whether the government maximizes tax revenue, welfare, or another objective.

[17]The government earn tax revenue:

$$R_G^{\tilde{T}}(\mathbf{p}, \boldsymbol{z}, \mathbf{x}, \mathbf{a}) = \sum_{i \in S_T \text{ and } x_i \leq \tilde{T}} \left[\delta^{x_i} \tau_{ix_i}^{handset} p_{x_i}^{handset} + \sum_{t \geq x_i}^{\tilde{T}} \left(\delta^t \tau_{it}^{usage} \sum_{j \in G_i \cap S_t} p_t^{a_{it}} \cdot \mathbb{E} d_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) \right) \right]$$

where S_t is the set of individuals with phones in month t, x_i represents i's adoption date, G_i represents the contacts of i, and $\mathbb{E}d_{ij}(\dots)$ represents the expected number of seconds of calls from i to j, and $\mathbf{a}$ represents the matrix of firm choices for each individual and month.

4.2. **Firms.** The entrant ($F = 1$), and then incumbent ($F = 0$) select a tower rollout plan $\mathbf{z}^F$ and a path of calling prices $\mathbf{p}^F = (p_t^F)_t$, earning profits through $\tilde{T}$:[18]

$$\pi_F^{\tilde{T}}(\mathbf{p}, \mathbf{z}, \mathbf{x}, \mathbf{a}, f) = R_F^{\tilde{T}}(\mathbf{p}, \mathbf{z}, \mathbf{x}, \mathbf{a}, f) - C_F^{\tilde{T}}(\mathbf{p}, \mathbf{z}, \mathbf{x}, \mathbf{a})$$

where $\mathbf{p} = [\mathbf{p}^0, \mathbf{p}^1]$, $\mathbf{z} = [\mathbf{z}^0, \mathbf{z}^1]$, $\mathbf{x} = [x_i]$ the vector of adoption dates, and $\mathbf{a} = [a_{it}]$ is the matrix of operator choices for each individual and month.

The entrant builds only urban towers ($\mathbf{z}^1 = \mathbf{z}_{(0\%)}$), following its parent company's articulated strategy in Africa (and later initial plan in Rwanda).[19] The incumbent builds urban towers, and also selects the proportion of rural towers r to build, ranked by population covered ($\mathbf{z}^0 = \{\mathbf{z}_{(100\%)}, \mathbf{z}_{(50\%)}\}$; see Figure 3[20]).

Firms may select calling prices as a multiple of the incumbent's baseline price path: $\mathbf{p}^F \in \psi \cdot \mathbf{p}^{base}$, given a choice from the grid $\psi \in \{0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1\}$. Firms must charge subscribers the same price for calls placed within the same network (on-net) and to the other network (off-net), an assumption that can be thought of as a rule imposed by the regulator.[21]

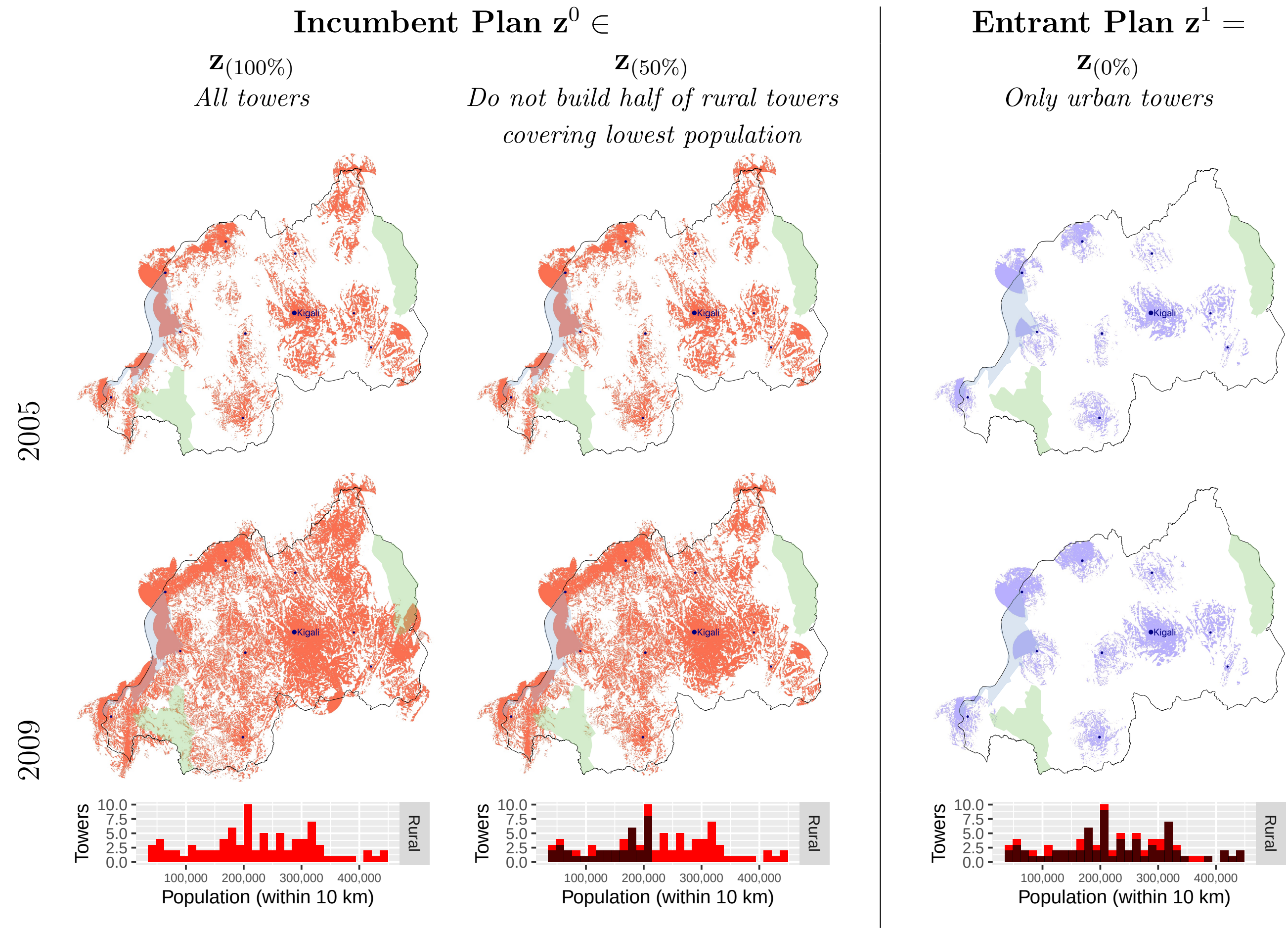
[18]This order of play matches what happened in Rwanda, where the entrant submitted its proposal for the new phase of competition first.

[19]Operator C's global Annual Report in 2010 said: 'There is scope for further coverage growth in our African markets, but urban centers currently represent the significant majority of the addressable population.'

[20]The Supplemental Appendix considers a wider set of options.

[21]While a rule to restrict off-net prices was not common in African markets at this time, it was proposed for Rwanda (Argent and Pogorelsky, 2011), and has been used in several countries to discipline competition (including Kenya, Singapore, Colombia, Turkey, Slovenia, and Portugal: see TMG, 2011). If instead operators charge different prices for on- and off-net calls, the game admits too many equilibria to be useful, because all cliques of individuals may tip into one network or the other.

FIGURE 3. **Rollout Plans**



Shows the coverage plans that operators may choose from. Starting from the its set of towers in 2005, the incumbent may build all towers ($\mathbf{z}_{(100\%)}$) or skip the half of rural towers covering the lowest population ($\mathbf{z}_{(50\%)}$). The entrant may build urban towers ($\mathbf{z}_{(0\%)}$). Coverage shaded; points denote cities. National parks shaded in light green; Lake Kivu shaded in light blue.

Firm F earns net revenue from the calls of its own subscribers, and from interconnection payments: firms pay each other f for each second their subscribers call in to the other network:

$$R_F^{\tilde{T}}(\mathbf{p}, \boldsymbol{z}, \mathbf{x}, \mathbf{a}, f) = \sum_{i \in S_T} \sum_{t \geq x_i}^{\tilde{T}} \delta^t \sum_{j \in G_i \cap S_t} \mathbb{E}\, d_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t(\mathbf{z}), \mathbf{a}) \cdot \Bigg[\overbrace{(1 - \tau_{it}^{usage}) p_t^F \cdot 1_{\{a_{it}=F\}}}^{\text{Subscribers}} + \underbrace{f \cdot \Big[1_{\{a_{it} \neq F \cap a_{jt}=F\}} - 1_{\{a_{it}=F \cap a_{jt} \neq F\}} \Big]}_{\text{Interconnection}} \Bigg]$$

where S_t is the set of individuals with phones in month t, G_i represents the contacts of i, $\mathbb{E}d_{ij}(\dots)$ represents the expected seconds that individual i calls j.[22]

Firm F incurs costs:

$$\begin{aligned} C_F^{\tilde{T}}(\mathbf{p}, \boldsymbol{z}, \mathbf{x}, \mathbf{a}) \quad &= K_{rural} \cdot \sum_{z \in \mathbf{z}^F, z \text{ is off grid}} \sum_{t \geq x_z^{tower}}^{\tilde{T}} \delta^t + \sum_{t \geq \min\{x_{\mathbf{z}^F}^{tower}\}}^{\tilde{T}} \delta^t fc^F \\ &+ \sum_{i \in S_T} \sum_{t \geq x_i}^{\tilde{T}} \delta^t \sum_{j \in G_i \cap S_t} \mathbb{E}d_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t(\mathbf{z}), \mathbf{a}) \cdot (ic_{L_i, onnet_{ij}}^{out} \cdot 1_{\{a_{it}=F\}} + ic_{L_j, onnet_{ij}}^{in} 1_{\{a_{jt}=F\}}) \end{aligned}$$

Firms act as though they rent rural towers, incurring an annualized cost of K_{rural} for owning and operation. Operator F incurs fixed cost fc^F each month. $ic_{L_i, onnet_{ij}}^{direction}$ is the incremental cost of sending or receiving an additional second for $direction \in \{in, out\}$. Costs vary by whether the two parties are on the same network, and between subscriber primary location ($L_i \in \{\text{urban}, \text{rural}\}$).[23]

4.3. **Consumers.** Given operator choices, each consumer decides when to adopt a phone (x_i), and each month which operator to use ($a_{it} \in \{0, 1\}$) and how many seconds to call each contact ($d_{ijt} \geq 0$).[24]

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[22] S_T represents the set of individuals who adopted phones in the baseline scenario by the end of the data (T).

[23] A tower is considered urban if it covers Kigali or one of Rwanda's 5 largest towns; a subscriber is considered urban if his most used tower is urban.

[24] For simplicity, consumers may only use one operator each month (single homing). In markets where different operators have low on-net prices and high off-net prices, consumers may hold accounts with

I extend the network demand system from Björkegren (2019) to allow individuals to choose between operators. The primary unit of observation is an account, which corresponds to a phone number. For ease of exposition I refer to accounts as individuals or nodes.[25] I observe the communication graph G_T^0, where a directed link $ij \in G_T^0$ indicates that i has called j by period T while both subscribed to the incumbent.[26] Define $G_i = \{j \,|ij \in G_T^0\}$ as i's set of contacts, and $S_t \subseteq N$ as the set of individuals with phones in month t. (See Discussion section for more on the network definition.)

Calling decision. Each period t, individual i draws a communication shock $\epsilon_{ijt} \overset{iid}{\sim} F_{ij}$ representing a desire to call each contact $j \in G_i \cap S_t$ that subscribes to either operator. These shock distributions, $\{F_{ij}\}_{ij \in G^T}$, encode the intensities of the links of the communication graph. In each period that i has a phone, he chooses a total duration $d_{ijt} \geq 0$ for that month, earning utility:

$$u_{ijt} = \max_{d_{ijt} \geq 0} \left[\frac{1}{\beta_{cost}} v_{ij}(d_{ijt}, \epsilon_{ijt}) - c_{ijt} d_{ijt} \right] \tag{1}$$

where $v(d, \epsilon)$ is the benefit of making calls of total duration of d, c_{ijt} the per-second cost, and β_{cost} a coefficient on cost (which converts between utils and money).

I model the benefit of making calls as:

$$v_{ij}(d, \epsilon) = d - \frac{1}{\epsilon} \left[\frac{d^\gamma}{\gamma} + \alpha d \right] \tag{2}$$

multiple operators to connect with contacts on different networks. Given that off-network pricing is restricted, there is less reason for consumers to hold multiple accounts.

[25] I assume that each account is associated with a unitary entity such as an individual, firm, or household; see Supplemental Appendix S1 and Björkegren (2019).

[26] G_T^0 is a subgraph of $\bar{G}$ the full communication graph of Rwanda (a directed social network), with N nodes representing all individuals in the country. A directed link $ij \in \bar{G}$ indicates that i would have a potential desire to call j via phone. I assume that links are fixed. Let $S_t \subseteq N$ be the set of individuals with phones in month t. I observe only individuals who adopt the incumbent by the end of my data T, the set $S_T^0 \subseteq N$. This will miss any links between subscribers where there is a latent desire to communicate but no call has been placed by T ($G_T^0 \subseteq \bar{G}_T^0$).

for $\epsilon > 0$, where the first term is a linear benefit; $\gamma > 1$ controls how quickly marginal returns decline, and $\alpha \geq 0$ controls how the intercept of marginal utility varies with the shock, and thus the fraction of months for which no call is placed.

The marginal cost of placing a call is affected by the choice of operator:

$$c_{ijt} = p_t^{a_{it}} + \beta_{coverage}\phi_{it}^{a_{it}}\phi_{jt}^{a_{jt}}$$

The second term represents the hassle cost when the caller or receiver have imperfect coverage.

The benefit of an additional second of duration across a link is decreasing, so i will call j until the marginal benefit equals the marginal cost, at duration:

$$d(\epsilon, \mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) = \left[\epsilon\left(1 - \beta_{cost}(p_t^{a_{it}} + \beta_{coverage}\phi_{it}^{a_{it}}\phi_{jt}^{a_{jt}})\right) - \alpha\right]^{\frac{1}{\gamma-1}} \tag{3}$$

which increases with the desire to communicate (ϵ) and decreases with cost. If the desire to communicate is not strong enough, i does not call: $d_{ijt} = 0$ when $\epsilon_{ijt} \leq \underline{\epsilon}_{ijt} := \frac{\alpha}{1-\beta_{cost}\left(p_t^{a_{it}}+\beta_{coverage}\phi_{it}^{a_{it}}\phi_{jt}^{a_{jt}}\right)}$.

Then, calls from i to j in period t have expected duration:

$$\mathbb{E}d_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) = \int_{\underline{\epsilon}_{ijt}}^{\infty} d(\epsilon, \mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) \cdot dF_{ij}(\epsilon) \tag{4}$$

and provide expected utility:

(5)
$$\mathbb{E}u_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) = \int_{\underline{\epsilon}_{ijt}}^{\infty} \left[d(\epsilon, \mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) \cdot \left(\frac{1}{\beta_{cost}}\left(1 - \frac{\alpha}{\epsilon}\right) - p_t^{a_{it}} - \beta_{coverage}\phi_{it}^{a_{it}}\phi_{jt}^{a_{jt}}\right) - \frac{1}{\beta_{cost}\epsilon}\frac{d(\epsilon, p_t, \boldsymbol{\phi}_t, \mathbf{a})^{\gamma}}{\gamma}\right] dF_{ij}(\epsilon)$$

Altogether, each month i uses operator a_{it}, he receives actual expected utility from each contact who has also adopted:

$$\mathbb{E}u_{it}(\mathbf{p}_t, \boldsymbol{\phi}_t, \boldsymbol{x}_{G_i}, \mathbf{a}) = \sum_{j \in G_i \text{ and } x_j \leq t} \mathbb{E}u_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) - s \cdot 1_{\{a_{it} \neq a_{it-1}\}} \tag{6}$$

where x_j represents j's adoption time and s the cost of switching operators.[27] However, at the point of adoption, i anticipates that having a phone in month t will provide utility:

$$\mathbb{E}\hat{u}_{it}(\mathbf{p}_t, \boldsymbol{\phi}_t, \boldsymbol{x}_{G_i}, \mathbf{a}) = \mathbb{E}u_{it}(\mathbf{p}_t, \boldsymbol{\phi}_t, \boldsymbol{x}_{G_i}, \mathbf{a}) + \eta_i^{a_{it}}(1-\delta)$$

where an individual's type (η_i^0, η_i^1) represents heterogeneity in the anticipated utility of using a phone on each operator that is unobserved to the econometrician. Types need not be mean zero, but each individual's type is constant over time and across counterfactuals. Each month that i does not have a phone he receives utility zero.

Adoption decision. Each individual i adopts at the first sufficiently attractive date, based on the actual paths of contact adoptions ($\boldsymbol{x}_{G_i}$), call prices (p_x), coverage ($\boldsymbol{\phi}_x$). He knows the current handset price ($p_t^{handset}$, inclusive of any tax), and has beliefs about future handset prices and contact operator choices. Adoption proceeds in two steps:

First, consumer i decides when to purchase a handset, expecting that adopting at time x with operator sequence $\mathbf{a}_i$ will yield utility:

$$\text{(7)} \qquad \mathbb{E}_t U_i^{x,\mathbf{a}_i}(\mathbf{p}, \boldsymbol{\phi}, \boldsymbol{x}_{G_i}, \hat{\mathbf{a}}_{G_i}) = \delta^x \left[\sum_{s \geq x}^{\infty} \delta^{s-x} \mathbb{E}\hat{u}_{is}(\mathbf{p}_s, \boldsymbol{\phi}_s, \boldsymbol{x}_{G_i}, [\mathbf{a}_i, \hat{\mathbf{a}}_{G_i}]) - \mathbb{E}_t p_x^{handset} \right]$$

under deterministic beliefs that in period $x > t$, the handset price will be $\mathbb{E}_t p_x^{handset}$, and that each contact j will use operator $\hat{\mathbf{a}}_j$, which will be defined later. i adopts in the first month x_i where he expects adopting immediately to be more attractive than waiting:

$$\text{(8)} \qquad \min\ x_i\ s.t. \left[\max_{\mathbf{a}_i} \mathbb{E}_{x_i} U_i^{x_i,\mathbf{a}_i}(\mathbf{p}, \boldsymbol{\phi}, \boldsymbol{x}_{G_i}, \hat{\mathbf{a}}_{G_i}) \geq \max_{s > x_i, \tilde{\mathbf{a}}_i} \mathbb{E}_{x_i} U_i^{s,\tilde{\mathbf{a}}_i}(\mathbf{p}, \boldsymbol{\phi}, \boldsymbol{x}_{G_i}, \hat{\mathbf{a}}_{G_i}) \right]$$

[27] In this model, consumers receive utility from the calls they place (which they pay for). Björkegren (2019) also considers the possibility that consumers also earn corresponding utility from the calls they receive (which are free), but finds these double count utility relative to the utility implied by the adoption decision.

Second, upon purchasing a handset, consumer i learns his contacts' operator choices (updating $\hat{\mathbf{a}}_j = \mathbf{a}_j$), and selects operator sequence $\mathbf{a}_i$ (maximizing Equation 7).

Consumer surplus. The net present value of consumer surplus through $\tilde{T}$ is:

$$U_{net}^{\tilde{T}} = \sum_{i \in S_T \text{ and } x_i \leq \tilde{T}} \left[\sum_{t \geq x_i}^{\tilde{T}} \delta^t \mathbb{E} u_{it}(\mathbf{p}_t, \boldsymbol{\phi}_t, \boldsymbol{x}_{G_i}, \mathbf{a}) - \delta^{x_i} p_{x_i}^{handset} + \delta^{\tilde{T}} p_{\tilde{T}}^{handset} \right]$$

which is net of calling, hassle, and handset costs.[28]

4.4. **Expectations.**

Firms. Given firm actions, there are many potential adoption equilibria. I restrict consideration to equilibria in which firms anticipate a degree of continuity in the subgame played by consumers. Specifically, consider indexing adoption equilibria by some index e. If consumers play an equilibrium of index e in the subgame resulting from actions $(\mathbf{p}^0, \mathbf{p}^1, \mathbf{z}^0, \mathbf{z}^1)$, firms believe that they will also play an equilibrium of index e in the subgame resulting from $(\mathbf{p}^{0'}, \mathbf{p}^{1'}, \mathbf{z}^{0'}, \mathbf{z}^{1'})$. Conditional on consumers adopting according to e, the overall equilibrium is unique.

Consumers. I focus on families of consumer adoption equilibria $\underline{e}^A$ and $\bar{e}^A$ along two dimensions. First, I index the speed of adoption: whether consumers adopt as slow ($\underline{e}$) or fast ($\bar{e}$) as possible given prices and coverage. Second, I index whether operator choices favor the incumbent ($A = 0$) or entrant ($A = 1$) (similar to Jia (2008)). Along these dimensions, adoption equilibria form a lattice.[29]

[28] I assume that at the end of the horizon, handsets are valued at the prevailing price.

[29] $\boldsymbol{x}$ has a lattice structure because $\mathbb{E}_t U_i^{\mathbf{a}_i, x_i}(\mathbf{p}, \boldsymbol{\phi}, \boldsymbol{x}_{G_i}, \hat{\mathbf{a}}_{G_i})$ is supermodular in $\boldsymbol{x}$ (Topkis, 1978; Milgrom and Shannon, 1994). i's optimal adoption date x_i is weakly monotonic in his type $\boldsymbol{\eta}_i$, contact's adoption date x_j, and contact's coverage $\phi_j^{a_j}$. Likewise, conditional on $\boldsymbol{x}$, $\mathbf{a}$ has a lattice structure because coverage choices are complementary. As long as coverage provided by the two firms is ordered (one weakly greater for all consumers), consumers weakly prefer to be on the same network as their contacts and $\mathbb{E}_t U_i^{\mathbf{a}_i, x_i}(\mathbf{p}, \boldsymbol{\phi}, \boldsymbol{x}_{G_i}, \mathbf{a}_{G_i})$ is supermodular in a_i and a_j, conditional on $\boldsymbol{x}_{G_i}$. Note that it may be possible to achieve lower or higher adoption, or more favor towards one operator, in the overall game by lifting the restriction of continuity in consumer adoption equilibria, if firms had sufficiently discontinuous off path beliefs. For example, if firms believe that when $\mathbf{p}^F \equiv \tilde{\mathbf{p}}$, consumers will adopt according to the fastest adoption equilibrium, but for $\mathbf{p}^F \neq \tilde{\mathbf{p}}$, consumers will adopt according to the slowest, this 'punishment' could induce firms to set a lower price than if they

Each month t, individuals learn the current handset price and expect handset prices in future periods to decline at an exponential rate consistent with the overall decline over this period: $\mathbb{E}_t p_x^{handset} = \omega^{x-t} p_t^{handset}$ for $\omega = \left(\frac{p_{\tilde{T}}^{handset}}{p_0^{handset}}\right)^{\frac{1}{\tilde{T}}}$. If an individual forecasts differently, the error will be captured in his type (η_i^0, η_i^1).[30]

Prior to purchasing a handset, i believes that each contact j will use the operator $\hat{\mathbf{a}}_j(\mathbf{p}, \boldsymbol{\phi})$ that is optimal given prices and coverage at j's location, for calls to the median individual at month T.[31]

4.5. **Equilibrium.** Given the incumbent's initial subscribers S_0 and towers, consumer types $\boldsymbol{\eta}$, interconnection fee f, and horizon $\tilde{T}$,

An equilibrium of index e is $(\mathbf{p}^0, \mathbf{p}^1, \mathbf{z}^0, \mathbf{z}^1, \mathbf{x}, \mathbf{a}, \mathbf{d})$ such that:

1. The entrant selects price sequence $\mathbf{p}^1$, and constructs urban towers $\mathbf{z}^1 = \mathbf{z}_{(0\%)}$, anticipating the choices of the incumbent and consumers:

$$\begin{aligned}
\mathbf{p}^1 = \arg\max_{\mathbf{p}^1} \pi_1^{\tilde{T}} \Bigg(& \mathbf{p}^{0*}(\mathbf{p}^1), \mathbf{p}^1, \mathbf{z}^{0*}(\mathbf{p}^1), \mathbf{z}^1, \\
& \mathbf{x}^* \left(\mathbf{p}^{0*}(\mathbf{p}^1), \mathbf{p}^1, \mathbf{z}^{0*}(\mathbf{p}^1), \mathbf{z}^1, \boldsymbol{\eta}, e \right), \\
& \mathbf{a}^* \left(\mathbf{p}^{0*}(\mathbf{p}^1), \mathbf{p}^1, \mathbf{z}^{0*}(\mathbf{p}^1), \mathbf{z}^1, \boldsymbol{\eta}, e \right), \\
& \mathbf{d}^* \left(\mathbf{p}^{0*}(\mathbf{p}^1), \mathbf{p}^1, \mathbf{z}^{0*}(\mathbf{p}^1), \mathbf{z}^1, \boldsymbol{\eta}, e \right), f \Bigg)
\end{aligned}$$

believed that consumers would adopt according to similarly optimistic or pessimistic equilibria in each subgame.

[30]Note that this structure implies that individuals do not anticipate how later adopters will respond to their actions, because later adopters may not condition their strategy on actions in prior periods. It also introduces a slight inconsistency: when i decides whether to adopt in period x_i, he does not know future handset prices, but does know the adoption dates of his future contacts, which will have incorporated future handset prices. I tolerate this inconsistency in order to have a computable notion of equilibrium.

[31]That is, $\hat{\mathbf{a}}_j(\mathbf{p}, \boldsymbol{\phi}) = \arg\min_a \left[p_T^a + \beta_{coverage} \phi_{jT}^a \phi_{mT}^{a_m} \right]$, for median individual m, who selects his operator analogously: $a_m = \hat{\mathbf{a}}_m(\mathbf{p}, \phi_m)$. In the Supplemental Appendix, I also consider approximate equilibria where consumers correctly anticipate contacts' operator choices; results are similar.

2. The incumbent selects price sequence $\mathbf{p}^0 = \mathbf{p}^{0*}(\mathbf{p}^1)$ and tower construction plan $\mathbf{z}^0 = \mathbf{z}^{0*}(\mathbf{p}^1)$, anticipating the choices of consumers:

$$
\begin{aligned}
\mathbf{p}^{0*}(\mathbf{p}^1), \mathbf{z}^{0*}(\mathbf{p}^1) = \arg\max_{\mathbf{p}^0,\mathbf{z}^0} \pi_0^{\tilde{T}} \Big(& \mathbf{p}^0, \mathbf{p}^1, \mathbf{z}^0, \mathbf{z}^1, \\
& \mathbf{x}^* \left(\mathbf{p}^0, \mathbf{p}^1, \mathbf{z}^0, \mathbf{z}^1, \boldsymbol{\eta}, e \right), \\
& \mathbf{a}^* \left(\mathbf{p}^0, \mathbf{p}^1, \mathbf{z}^0, \mathbf{z}^1, \boldsymbol{\eta}, e \right), \\
& \mathbf{d}^* \left(\mathbf{p}^0, \mathbf{p}^1, \mathbf{z}^0, \mathbf{z}^1, \boldsymbol{\eta}, e \right), f \Big)
\end{aligned}
$$

3. Consumers adopt at times $\mathbf{x} = \mathbf{x}^*(\mathbf{p}, \boldsymbol{z}, \boldsymbol{\eta}, e)$, using operators $\mathbf{a} = \mathbf{a}^*(\mathbf{p}, \boldsymbol{z}, \boldsymbol{\eta}, e)$ and placing calls $\mathbf{d} = \mathbf{d}^*(\mathbf{p}, \boldsymbol{z}, \boldsymbol{\eta}, e)$ such that:

- Each initial adopter $i \in S_0$ selects operator sequence $\mathbf{a}_i \in \{0,1\}^{\bar{T}}$ optimally, believing each contact j will adopt at time x_j using operators $\mathbf{a}_j$
- Every other observed adopter $i \in S_T \backslash S_0$ believes each contact j will adopt at time x_j, and selects:
  - adoption date $x_i \in \{1, ..., \bar{T}\}$ optimally, believing j will use predicted operator $\hat{\mathbf{a}}_j(\mathbf{p}, \boldsymbol{\phi}_j, \boldsymbol{\phi}_{median})$
  - operator sequence $\mathbf{a}_i \in \{0,1\}^{\bar{T}-x_i}$ optimally, believing j uses operators $\mathbf{a}_j$
- Each month t after adopting, i calls contact j for $d_{ijt} = \mathbb{E} d_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a})$ seconds

4.6. **Discussion.**

Dark network. In the transaction data I do not observe the 'dark' network of individuals $i \in N \backslash S_T$ that did not become customers of the incumbent by T, nor latent links ij would have only become active had conditions been more favorable. This would cause me to underestimate demand if counterfactual calling prices were lower than what I observe in my data. Since prices were declining over this period, I limit the impact by computing counterfactuals through shorter horizons $\tilde{T} \leq T$ during which counterfactual prices would be no more favorable than observed conditions through T.[32] Main results use a horizon computed using variation in both handset and calling prices using the structural model and a representative survey covering part of the dark network (RIA, 2012); the Supplemental Appendix reports a conservative horizon limited to the observed variation in calling prices.[33] Additionally, I assume that subscribers of the poorly run competitor (Operator B) do not change their decisions in counterfactuals; this will tend to attenuate the effects of competition.

Firm action spaces. I restrict firm action spaces in three respects:

I offer firms only options that are reasonable in the long term, to limit the impact of observing a finite horizon. Firms neglect the value of their accumulated stock of subscribers after $\tilde{T}$. As a result, my results may underestimate incentives to invest. I assess results for a long horizon (4 years), and assess different horizons in the Supplemental Appendix.

I rule out the possibility that either firm would build towers in locations that were not served under the baseline scenario, because it would be difficult to predict demand in those locations. These are few: the incumbent's actual rollout plan ($\mathbf{z}_{(100\%)}$) was nearly complete (see Figure 3).

I rule out strategies where firms divide up the country to serve different rural areas, because adoption equilibria form a lattice only if coverage provided by the two firms are ordered (one weakly greater for all consumers). In other countries in the region it is common for firms to be ordered in terms of coverage, with the lowest quality firms offering coverage only in cities.[34]

[32]This is akin to speeding up a film using fast forward, but pausing before it runs out of tape.
[33]For more details and definitions of these horizons, see Supplemental Appendix S5.
[34]See Supplemental Appendix for more evidence on this.

TABLE 3. Additional Parameters

Parameter		Value	Source
Consumer Preferences			
Switching Cost	s	\$36.09	Hypothetical switching exercises
Idiosyncratic operator preference			
… Mean	$m(\{\eta_i^0 - \eta_i^1\})$	\$2.45	Hypothetical switching exercises
… SD	$\sigma(\{\eta_i^1 - \eta_i^0\})$	\$6.72	Hypothetical switching exercises
Firm Costs			
Cost of operating a tower	K_{rural}	\$80,584/year	Regulator study RURA (2011)
Incremental cost	$ic^Y_{L_i,onnet_{ij}}$	*	Interconnection study PwC (2011)
Fixed cost	fc^F	*	Interconnection study PwC (2011)

*: The study was provided under the condition that it remain confidential. See Appendix A for discussion and validation.

5. Estimation

The main demand parameters (F_{ij}, γ, α, β_{cost}, $\beta_{coverage}$, $\underline{\eta}_i^0, \bar{\eta}_i^0$) are estimated in Björkegren (2019) under the baseline scenario. These elasticities will determine how subscribers trade off price and coverage offerings (both at his own and contacts' locations).

Switching costs (s) and the distribution of idiosyncratic operator preferences ($\{\eta_i^0 - \eta_i^1\}$) were estimated from hypothetical switching exercises in a survey of 89 Rwandan phone owners. Firm costs (K_{rural}, $ic^Y_{L_i,onnet_{ij}}$, fc^F) were calibrated based on regulator studies. See Table 3 for parameter values and Appendix A for details.

6. Simulation

The incumbent's initial subscribers and towers are taken as given. Given policy choices f, equilibrium index $e \in \{\underline{e}^A, \bar{e}^A\}$, and individual types $\boldsymbol{\eta}$, I compute an equilibrium in three nested steps:

(1) **Consumer choices**

For a grid of price choices $(\mathbf{p}^0, \mathbf{p}^1)$ and rollouts $\boldsymbol{z}^0$, I compute an adoption equilibrium using an iterated best response method that has two stages:

(a) *Adoption dates* $\mathbf{x}$: I initialize with a candidate adoption path representing a complete delay of adoption for $\underline{e}^A$ ($\mathbf{x} = \bar{T}$), or immediate adoption for $\bar{e}^A$ ($\mathbf{x} = 0$). Each individual optimizes their adoption date x_i, conditional on the adoption dates of others $\mathbf{x}_{-i}$ and beliefs about others' operators $\hat{\mathbf{a}}_{-i}(\mathbf{p}, \boldsymbol{\phi}_{-i}, \boldsymbol{\phi}_{median})$, until $\mathbf{x}$ converges.

(b) *Operators* $\mathbf{a}$*:* Conditional on equilibrium adoption dates $\mathbf{x}$, I initialize with all individuals subscribing to operator A ($\mathbf{a} \equiv A$). Each individual optimizes their operator choice $\mathbf{a}_i$, conditional on the operator choices of others ($\hat{\mathbf{a}}_{-i} = \mathbf{a}_{-i}$), until $\mathbf{a}$ converges.

(2) **Incumbent choices**

The incumbent selects $\mathbf{p}^0(\mathbf{p}^1)$ and $\boldsymbol{z}^0(\mathbf{p}^1)$ to maximize profits through $\tilde{T}$, anticipating consumer choices in equilibrium e.

(3) **Entrant choices**

The entrant selects $\mathbf{p}^1$ to maximize profits through $\tilde{T}$, anticipating incumbent and consumer choices in equilibrium e.

For the lower equilibrium $\underline{e}^A$, I set individuals' types to their lower bound ($\boldsymbol{\eta} = \underline{\boldsymbol{\eta}}$), to recover a lower bound of the adoption equilibrium. For the upper equilibrium $\bar{e}^A$, I set individuals' types to their upper bound ($\boldsymbol{\eta} = \bar{\boldsymbol{\eta}}$) to recover an upper bound.[35] For simplicity, I assume that consumers may switch operators at most once.

Idiosyncratic preferences for the entrant are treated as random parameters: for each individual I draw $\Delta\eta_i \overset{iid}{\sim} N\left[m(\eta_i^0 - \eta_i^1), \sigma(\eta_i^1 - \eta_i^0)\right]$, and compute $[\underline{\eta}_i^1, \bar{\eta}_i^1] = [\underline{\eta}_i^0 - \Delta\eta_i, \bar{\eta}_i^0 - \Delta\eta_i]$. I present results from a single random draw and assess the effect of the random draw in the Supplemental Appendix.

[35]See Supplemental Appendix S6 for pseudocode.

7. The Effects of Competition

I consider counterfactuals that allow entry earlier, under different interconnection rates and number portability. I report outcomes on prices, towers built, returns on investment (ROI), consumer surplus, profits, government revenue, and total welfare.

The main simulation results are reported in Table 4 (low equilibrium in Panel A, high equilibrium in Panel B) and Figure 4.

In the main text, I focus on incumbent favoring equilibria and refer to the lowest equilibrium outcomes ($\underline{e}^0$) in text (and place the highest equilibrium $\bar{e}^0$ outcomes in parentheses, or omit if identical). I present results up to December 2008 (which under a model of the dark network would not be affected by the omission of dark nodes for prices as low as 20% of the baseline price path).

I find:

7.1. **Competition lowers prices and can increase incentives to invest.** I consider introducing competition under a focal interconnection rate of $f = \$0.11$ in Table 4 row 2. Under this policy, the incumbent would reduce prices to 70% (60%) of the baseline price path, and the entrant to 60% (50%).[36] The incumbent would have still built all rural towers, and in the next section I find that incentives to invest increase.

This lowers profits for the incumbent but has a large impact on consumer surplus. Altogether, the total welfare provided by the mobile phone system would have increased by 33% (38%; comparing row 1 and row 2). This increase in welfare is an amount equivalent to 1% of GDP or 3-5% of official development aid in Rwanda over the same period.[37]

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[36] The price series is shown in Figure 2.

[37] Over the horizon from 2005-2008, in the baseline scenario the incumbent provided a social surplus of \$334m (\$386m), an amount equivalent to 2-3% of Rwanda's GDP over the same time period. In this equilibrium, the entrant earns slightly negative profits. This suggests that sustaining this market structure may require subsidizing the entrant on the order of \$8m (4% of the total welfare generated), or the promise of an acquisition or additional future profits as the network grows.

Table 4. Market Outcomes as Function of Competition Policy

Policy			Outcomes (January 2005-December 2008)					
Panel A	Inter-	Switch.	Call Prices		C.	Incumbent	Entrant	Gov.
Low Equilibrium ($\underline{e}^0$)	connect	Cost			Surplus	Profit	Profit	Revenue
	f	s	$\frac{\mathbf{p}^0}{\mathbf{p}^{base}}$	$\frac{\mathbf{p}^1}{\mathbf{p}^{base}}$				
	\$/min	\$			\$m	\$m	\$m	\$m
Baseline Scenario	-	-	1.00	-	168	108	0	58
Additional Competitor								
Entry 1/2005	0.11	36	0.70	0.60	281	98	5	62
...inc. or firms jointly select interconnect	0.33	36	0.80	0.80	237	109	-1	62
...number portability	0.11	19	0.50	0.50	383	88	-1	61
Entry 7/2008	0.11	36	0.70	0.40	259	97	2	59

Panel B	Inter-	Switch.	Call Prices		C.	Incumbent	Entrant	Gov.
High Equilibrium ($\bar{e}^0$)	connect	Cost			Surplus	Profit	Profit	Revenue
	f	s	$\frac{\mathbf{p}^0}{\mathbf{p}^{base}}$	$\frac{\mathbf{p}^1}{\mathbf{p}^{base}}$				
	\$/min	\$			\$m	\$m	\$m	\$m
Baseline Scenario	-	-	1.00	-	194	126	0	66
Additional Competitor								
Entry 1/2005	0.11	36	0.60	0.50	365	103	2	68
..firms jointly select interconnect	0.43	36	0.90	0.90	226	128	-1	68
..inc. selects interconnect	0.33	36	0.90	0.90	226	127	-1	68
...number portability	0.11	19	0.60	0.50	366	100	5	68
Entry 7/2008	0.11	36	0.70	0.30	284	108	2	65

Each row presents the outcomes under a given policy, for incumbent favoring equilibria. Profits omit fixed costs of operation and license fees. Utility and revenue reported in 2005 U.S. Dollars, discounted at a rate of δ. Consumer surplus includes the surplus utility each individual receives from the call model through December 2008, minus the cost of holding a handset from the time of adoption until December 2008.

7.2. **Compatibility introduces a tradeoff between prices and incentives to invest.** This focal interconnection rate of f = \$0.11 is slightly higher than recommendations at that time (f = \$0.07 (RURA, 2006) or \$0.09 (PwC, 2011)), and zero rating (f = \$0: 'bill and keep', to which the U.S. is transitioning (FCC, 2019)).

Figure 4 shows results as a function of the interconnection rate. The left column shows outcomes under the baseline scenario; and the right column when an additional competitor is granted a license at month $t = 0$ under different interconnection rates (shown decreasing with the x-axis).[38]

If firms are allowed to select the interconnection rate (to maximize the profits of either the incumbent, or the two firms jointly), they will set it high (f = \$0.33 or \$0.43, beyond the bounds of Figure 4 but shown in Table 4 rows 3/4). That would mute the effect of competition on prices (80-90% of baseline scenario) and welfare.[39] This is reminiscent of many emerging network goods, where interconnection does not arise endogenously (Katz and Shapiro, 1985), as well as theoretical results that firms may use the interconnection rate as an instrument of collusion (Armstrong, 1998; Laffont et al., 1998).

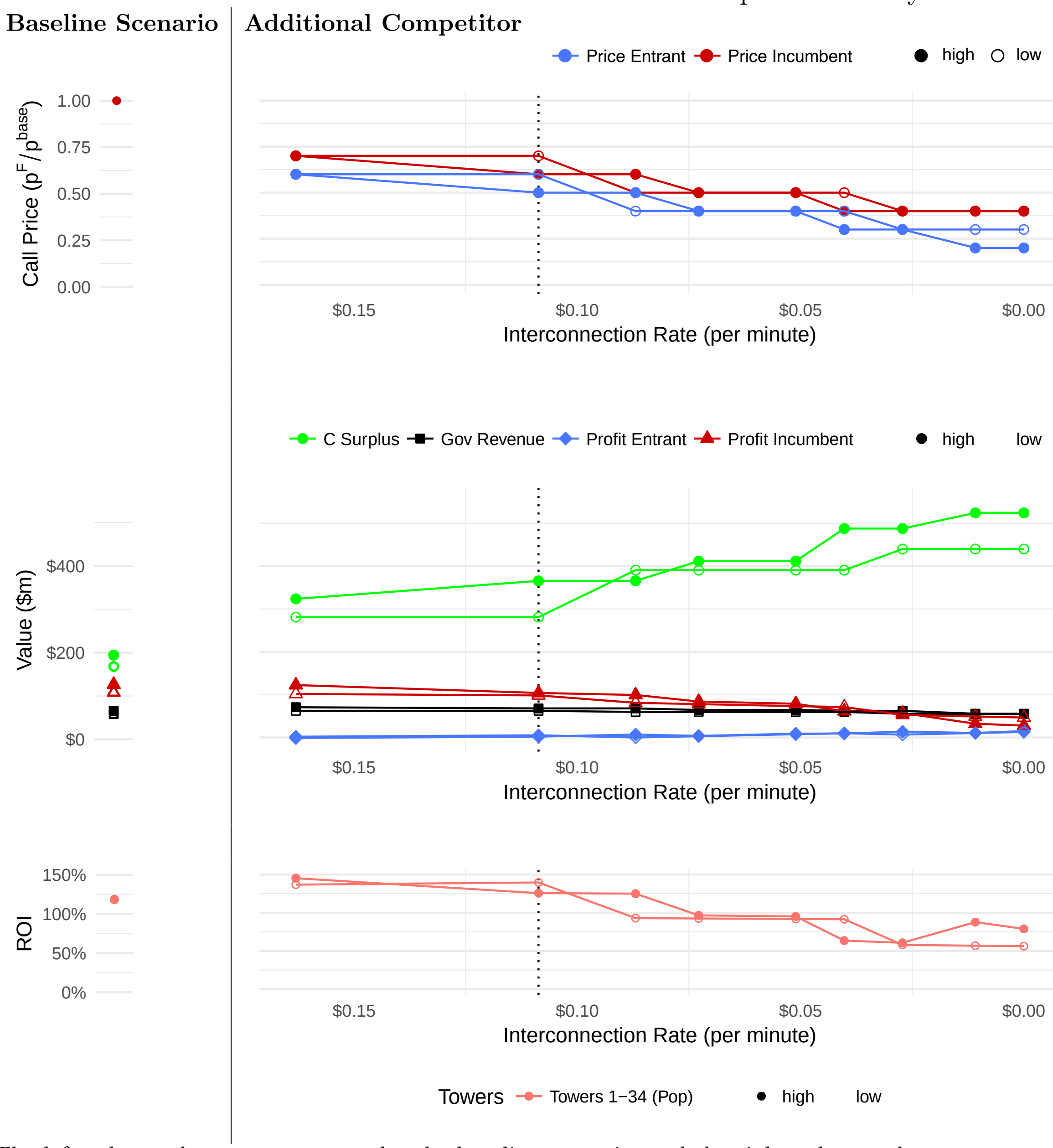
As the interconnection rate is lowered, price competition becomes more intense (top panel), and welfare increases and incumbent profits decline (middle panel). This is because interconnection fees soften price competition: when a firm lowers prices, its subscribers call both networks more, but the firm has to pay the interconnection fee on calls to the competing network.

To more finely investigate investment, I evaluate the ROI of building rural towers (bottom panel). I start from equilibria where the incumbent is forced to omit building

[38] Results tables omit fixed costs, which based on accounting I estimate to lie between \$1-16m for the entrant and are included in welfare estimates in the text. Results also omit license fees, which represent additional transfers to the government. The government charged the entrant \$4m per year to operate its network when it did enter. Normal form game boards are shown in the Supplemental Appendix.

[39] I allow the incumbent to select the interconnection rate on a grid from \$0.00 to \$0.43. Results may differ if firms could set separate prices for on- and off-net calls.

FIGURE 4. Market Outcomes as Function of Competition Policy



The left column shows outcomes under the baseline scenario; and the right column when an additional competitor is granted a license at month $t = 0$ under different interconnection rates (shown decreasing with the x-axis). Outcomes computed from January 2005 through horizon December 2008. Dotted line denotes a focal interconnection rate that balances competitive pressure with incentives to invest. Filled marks denote high equilibrium and open marks denote low equilibrium. Red represents incumbent and blue entrant. All equilibria shown have entrant moving first, and consumers favoring incumbent. Outcomes reported in 2005 U.S. Dollars, discounted at a rate of δ. Consumer surplus includes the surplus utility each individual receives from the call model through December 2008, minus the cost of holding a handset from the time of adoption until December 2008.

rural towers ($\mathbf{z}^0 = \mathbf{z}_{(50\%)}$), and then compute the returns to building the full set of towers ($\mathbf{z}_{(100\%)}$), allowing consumers to change adoption dates, operators, and usage. The ROI tends to decline as the interconnection rate is lowered, but starts above the level of the baseline scenario, and is always positive, suggesting that investment would always be profitable. Under the focal interconnection rate of $f = \$0.11$ (shown in a dotted line), competition increases ROI *above* the baseline scenario.

7.3. **Incentives to invest are driven by business stealing.** To more deeply understand investment effects, I further decompose these incentives to build low population towers. Starting from equilibria where the incumbent is forced to omit building rural towers ($\mathbf{z}^0 = \mathbf{z}_{(50\%)}$), I compute the returns to building the full set of towers ($\mathbf{z}_{(100\%)}$) in two stages. First, I allow consumers to change adoption dates and usage, but hold fixed the choice of operator. Then, I allow consumers full choice over usage, adoption, and operator. I first consider the focal interconnection rate ($f = \$0.11$). Table 5 reports the incumbent's incremental profits and ROI from building rural towers. There are three forces:

1. Competition lowers overall revenues. Because prices are lower, total profits to the industry from building the towers are 43% (50%) lower under competition (Table 5 rows 1-2).[40]

2. Competition splits network effects between operators. Only a small amount of benefits spill over into the entrant's network: the incumbent still captures 95% (100%) of the profits from investing, when operator choices are held fixed (Table 5 row 3).

Of the additional revenue that accrues to the entrant, 89% (98%), accrues at the network border (entrant's off-net calls). These spillovers can partially be recouped:

[40]Note that if the incumbent were allowed to charge different prices in different geographies it might earn higher profits by keeping prices high in rural areas, where it faces less competition. Industry net revenue declines from \$1.27m (\$1.23m) under the baseline scenario to \$0.73m (\$0.62m) combined between operators under competition. The additional operator also provides a small amount of idiosyncratic differentiation, based on the idiosyncratic draw $\Delta\eta_i$, although this effect is negligible.

Table 5. Return on Tower Investment

	Equilibrium Call Prices		Impact of Inc. Building Low Pop Density Towers ΔProfit		ROI	
	$\frac{\mathbf{p}^0}{\mathbf{p}^{base}}$	$\frac{\mathbf{p}^1}{\mathbf{p}^{base}}$	Incumbent $m	Entrant $m	Incumbent	Social
<u>**Full Model**</u>						
Baseline Scenario	**1.00, 1.00**	-	**1.27, 1.23**	-	**0.98, 1.00**	**6.64, 6.49**
Additional Competitor:						
Interconnection $0.11/min	**0.70, 0.60**	**0.60, 0.50**	**2.16, 1.87**	**-1.43, -1.25**	**1.40, 1.26**	**7.74, 7.96**
...fixing operator			0.39, 0.22	0.02, 0.00	0.43, 0.25	6.89, 6.92
...add'l effect of operator choice			1.60, 1.65	-1.29, -1.26	-	-
Interconnection $0	**0.40, 0.40**	**0.30, 0.20**	**0.88, 2.82**	**-0.55, -0.26**	**0.56, 0.79**	**8.01, 10.45**
...fixing operator			0.19, -0.29	0.05, 0.03	-0.21, -0.37	6.90, 5.99
...add'l effect of operator choice			1.07, 3.10	-0.61, -0.29	-	-

Impact cells report the negative of the difference in outcomes between the equilibrium where the incumbent is constrained to not build the 50% lowest population rural towers, and the new adoption equilibrium that results when those towers are built, for the low and high equilibria. Outcomes computed from January 2005 through horizon December 2008. 'Fixed operator' allows consumers to change adoption dates and usage but holds operator choices fixed; consumers who originally switch operators do so on the latest of the original switch date and the new adoption date. Under zero interconnection in the high equilibrium, ROI is lower despite higher profits because costs are substantially higher. Social ROI represents consumer surplus, government revenue, and firm profit, relative to firm costs. ROI is not relevant for the incremental effect of operator choice since the cost of the towers has already been accounted for. Utility and revenue reported in 2005 U.S. Dollars, discounted at a rate of δ. Consumer surplus includes the surplus utility each individual receives from the call model through December 2008, minus the cost of holding a handset from the time of adoption until December 2008.

56% (76%) is paid back through interconnection fees. However, 11% (2%) of the revenue results from spillovers in the interior of the entrant's network (entrant on-net calls). Interconnection fees do not adjust for these interior spillovers because they are incurred only at the boundaries of the two networks.[41]

[41]The magnitude of these internal spillovers will depend on the shape of the entrant's network, as well as the degree of network spillovers: they require the entrant's network to be both porous to adoption spillovers, and sufficiently deep that spillovers reach beyond the border.

3. A business stealing motive increases incentives to differentiate quality. Investing induces marginal consumers to switch networks, shown when consumers are allowed to change operators (Table 5 row 4).

Altogether, the business stealing effect dominates: it effect accounts for 80% (88%) of the profit the incumbent earns from the investment, dwarfing the lost network effects.

The incumbent's ROI under competition is 1.40 (1.26): larger than the returns under the baseline scenario of 0.98 (1.00). Although competition reduces the incumbent's total profit, it can *increase* the marginal returns to an investment that retains customers who otherwise would switch. Private ROI under either market structure is far lower than the social ROI of as much as 7.74 (7.96), suggesting this market may see underinvestment.

Discussion. The effect of competition on investment depends on several factors:

First, it depends on the competition policy. Under an interconnection rate of zero ('bill and keep'), the private ROI decreases below the baseline scenario level to 0.56 (0.79) because prices are lower and the incumbent does not earn interconnection fees for the benefits it provides to the other network (Table 5 rows 5-7).

Second, it also depends on the relative size of network and business stealing effects. The latter depends on how the investment interacts with consumer preferences. The consumers who switch networks in response to tower investment are the urban consumers who spend a fraction of their time in rural areas (see Figure A1).

7.4. **Number portability increases the level of competition.** Policies that allow consumers to port their phone numbers between operators have been planned or implemented by 40% of developing country regulators (GSMA, 2013).[42] My consumer

[42]Rwanda initially planned to introduce portability when mobile operators reached combined 60% market penetration, but as of this writing has yet to do so.

survey suggests that number portability would lower users' cost of switching operators from \$36.09 to \$18.51. Number portability lowers prices, incumbent profits, and increases consumer surplus in the lower equilibrium but has muted effects in the upper (Table 4 second to last rows of each panel).[43] Given the choice, the incumbent would elect to maintain high switching costs.

7.5. **Robustness.** If entry of the competitor is delayed until July 2008 (5 months before the end of the horizon), the entrant sets lower prices (40% (30%) of baseline price path), the incumbent keeps prices weakly higher (70%), and the total impact on welfare is smaller (Table 4 last rows of each panel).

I assess several alternate specifications in the Supplemental Appendix (S8-S14):

ROI for tower construction is weakly larger under the focal competition policy for an expanded set of rollout plans ($\mathbf{z}^0 \in \{\mathbf{z}_{(100\%)}, \mathbf{z}_{(75\%)}, \mathbf{z}_{(50\%)}, \mathbf{z}_{(25\%)}, \mathbf{z}_{(0\%)}\}$ versus $\mathbf{z}^1 = \mathbf{z}_{(0\%)}$) in a partial equilibrium analysis that holds prices fixed. The 10 towers built under government coverage obligation that were unprofitable under the baseline (Björkegren, 2019) are profitable under this competition policy, suggesting that in some settings competition may substitute for access regulation.

Results are similar under different time horizons ($\tilde{T}$). A conservative time horizon (through Dec 2005) sees analogous price reductions and welfare increases.[44] Under a longer horizon through period T plus that final month played repeatedly for 3 years, competition increases ROI even for lower interconnection rates. Results are similar to the main results under different draws of the random preferences $[\underline{\eta}_i^1, \bar{\eta}_i^1]$, and under entrant favoring equilibria. If at the point of adoption, consumers exactly anticipate which operators their contacts will select ($\hat{\mathbf{a}}_j \equiv \mathbf{a}_j$), consumer decisions are no longer guaranteed to reach equilibrium, but outcomes are similar under an approximate

[43] This distinction between the low and high equilibrium is likely due to the grid of choices.

[44] The conservative time horizon covers the construction of few rural towers, so is not well suited to answering questions about investment.

notion of equilibrium. Results are similar if the incumbent moves before the entrant or if the firms move simultaneously, but are less stable for this grid of prices.

Simpler demand systems can substantially mischaracterize results. Ignoring the dependence between individuals' decisions results in underestimating the revenue from building towers by 52% (56%); considering links as stochastic draws (Ryan and Tucker, 2012) results in overestimating it by as much as 86%.

I find similar welfare effects in the monopoly model if, rather than facing an entrant, the incumbent were simply forced to lower its price to the later competitive level.

8. Conclusion

Societies are grappling with an increasing number of industries characterized by network effects. This paper simulates the effects of competition policy in a network industry of particular importance to developing societies, mobile phone networks. I demonstrate how data from a dominant incumbent can be used to estimate the effects of a variety of competition policies. My method captures how changes ripple throughout networks and across network boundaries, and can thus assess how the policy environment affects incentives to invest.

I find that competition in the Rwandan mobile phone industry has a large scope to affect welfare. Policies to increase competition have mixed effects on incentives to invest: they split the revenue generated by rural towers, but for high enough interconnection rates this effect is dominated by increased returns from differentiating quality. It is an open question whether these results would be similar for mobile internet, which still has low penetration in much of Africa. While I focus on the primary investments in this network, in rural towers, network firms have a menu of potential investments which would be differentially affected by competition. Competition will tend to make investments that induce a marginal customer to switch more attractive, and investments that induce dispersed network spillovers less attractive. Competition is thus likely to affect the nature of network products provided by the market.

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Appendix A. Additional Parameters

Additional demand parameters. I estimate demand parameters using the survey of 89 mobile phone subscribers.

Switching operators entails changing phone numbers, coverage, and learning new short code commands. The mean switching cost is s = \$36.09 (s.e. \$6.03), corresponding to 6.8 months of household average airtime spending in 2010 (EICV). Roughly half of that cost (\$17.58) arises from having to change phone numbers. High switching costs are commonly found in the literature (Handel and Schwartzstein, 2018).

Holding fixed prices and coverage, consumers have a slight idiosyncratic preference for the incumbent, with a difference with mean $m(\eta_i^0 - \eta_i^1) = \$2.45$ (\$0.01 per month), and standard deviation $\sigma(\eta_i^1 - \eta_i^0) = \$6.72$. These preferences are not correlated with observables, and when asked to explain their choices, the most common response was a preference for one operator's branding or color scheme.

Validation. I validate the quality of hypothetical responses by comparing to an analogous choice observed in the data. It is much less costly to switch between plans on the same operator; actions in the data are consistent with an intraoperator switching cost of \$6.83. I find that this does not differ significantly at the 1% level from the estimate formed from analogous hypothetical choices.[45] The survey estimated parameters do not have a major effect on results: idiosyncratic preferences are very close to zero, and in counterfactuals I find that dropping the switching cost to \$18.51 does not have a major effect on results. Supplemental Appendix S4 assesses the extent to which the model matches behavior observed later in Rwanda, and in countries that were competitive at this time.

[45] For part of this time, the operator offered plans billed by the minute or the second, see Björkegren (2014). I model the introduction of per second billing in 2006 as a price decline.

Firm costs. I use firm costs from two Rwandan regulator studies.

I use accounting fixed costs fc^F and the incremental costs of scaling the size of the network $ic^Y_{L_i,onnet_{ij}}$ from PwC (2011), a confidential cost study commissioned to set interconnection rates. This study constructs an engineering breakdown of the network, using cost estimates obtained from operators, crosschecked against international benchmarks.[46] It combines the costs of towers, switching equipment, staff, central operations, and capital to compute the Long Run Incremental Cost (LRIC) of operating a network that can serve an additional second of voice.[47] I break down these costs to better match my setup, in three ways. First, the study inflates the incremental cost estimates with a proportional markup to cover fixed costs of operating the network. I report these fixed costs separately, by multiplying each firm's total incremental cost by the same proportional markup used in the study (50%) after identifying the size of the firm in equilibrium.[48] Second, I remove the license fee paid to the regulator, which is a pure transfer. Third, I separate out the cost of rural tower investments. For subscribers who primarily use urban towers ($L_i = urban$), I include the cost of towers in incremental costs, as urban tower construction tends to scale with call volumes. For subscribers who primarily use rural towers ($L_i = rural$), I compute the cost of towers separately, as rural tower construction scales with coverage.

I use the annualized cost of building and operating a rural tower, K_{rural}, from RURA (2011), a public study commissioned to set the regulated prices of infrastructure sharing based on cost data from operators.[49]

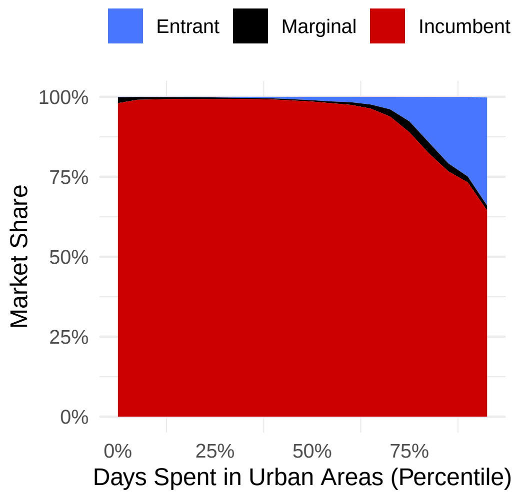
[46]PwC (2011) replaced cost items that did not seem consistent with average estimates the firm had collected from 7 other operators in Africa and the Middle East, omitting outliers.

[47]While marginal costs are in many cases zero in telecom, LRIC is more representative of the shifts in costs that would be expected over the range of network scales I consider.

[48]Although these accounting fixed costs may differ from economic fixed costs, conditional on introducing a competitor, fixed cost estimates do not affect firm behavior. The entrant's fixed cost does affect the welfare gains of introducing a competitor.

[49]The total annualized cost of owning and operating a tower is \$51,000 per year, plus \$29,584 for rural towers powered by generators. This includes operating expenses, depreciation, and a 15% cost of capital. Assumed lifespans are 15 years for towers, 8 for grid access, and 4 for generators.

FIGURE A1. Effects of Investment
Market Share and Marginal Users



The incumbent dominates market share among rural users; the entrant attracts away urban users. When the incumbent builds rural towers (changing the rollout plan from $\mathbf{z}_{(50\%)}$ to $\mathbf{z}_{(100\%)}$), it induces the highlighted marginal group of users to switch from the entrant to the incumbent. These marginal users spend most but not all of their time in urban areas, with the remainder in rural areas. Interconnection rate \$0.11/min, low equilibrium, incumbent favoring (the high equilibrium is visually indistinguishable).

Validation. Because Rwanda's regulator does not intervene in consumer telecom prices, the monopolist's price choices allow a consistency check. Under these cost estimates, the monopolist's chosen prices are profit maximizing.[50] Although the cost estimates behind most interconnection studies are confidential, the resulting interconnection rates recommended by PwC (2011) are similar to those recommended on average in Africa (\$0.07 vs. \$0.08 per minute; Lazauskaite (2009)), suggesting costs are similar to other African markets.

[50]See Supplemental Appendix S7.