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Competition in network industries: Evidence from the Rwandan mobile phone network

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This article 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 consumers' utility from adopting and using mobile phones, with transaction 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. However, forcing free interconnection can lower incentives to invest.

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 goods with direct network effects, whose users value links with other users (such as communication, payment, or social networks).[1] This article focuses on emerging economies, where telecom networks have

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[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 inconclu-

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 sector's development (World Bank, 2004), and regulators have little guidance on when to tilt favor, allow consolidation (Moody's, 2015), or split firms (Reuters, 2017).

This article 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 demand model for network goods 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 that adding a competitor could have increased incentives to invest, and increased welfare by the equivalent of 1% of GDP. Although there are a number of empirical studies of competition between goods with indirect network effects (for example, Rysman, 2004; Dubé, Hitsch, and Chintagunta, 2010), to my knowledge this represents the first empirical analysis of competition between goods with direct network effects using micro data.[3]

Like most African countries, Rwanda initially licensed a monopoly mobile phone operator (Incumbent, in 1998: Operator A), and gradually allowed the entry of additional operators (Williams, Mayer, and Minges, 2011).[4] Each firm was required to interoperate so consumers could call customers of other networks, but each customer could use only the coverage of the firm they subscribed to. I use data from the period 2005–2009 during which the regulator allowed entry of a second firm (Operator B), which ended up being poorly run and never captured much market share. Despite this entrant's weaknesses, during this period, 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 almost the entire network of mobile phones at the time, and each call over those 4.5 years. Immediately after this period (at the end of 2009), the regulator granted an additional license to a well-managed competitor (Operator C: Entrant), which built coverage in lucrative urban markets, charged lower prices, and captured market share.

Could the government have done better by granting Operator C a license at the beginning of the period (in 2005)? I answer this question using an empirical model that proceeds in three stages.

First, the government chooses whether to grant a license to an additional competitor. If so, the government selects the interconnection rate that each firm pays the other when its subscribers call into their network. I assume that the government requires firms to charge users 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 relative to the baseline policy.

Second, firms choose from a menu of strategies. The entrant plans to build 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.

sive (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 telecom partner's parent's African revenue in 2017 (including two small operations outside of Africa).

[3] In a related article, Weiergraeber (2021) studies network effects and switching costs in a demand model for US mobile phones, using data on segment- and region-specific market shares, though that article does not model supply.

[4] I am unable to reveal the names of the operators due to a confidentiality restriction with the data.

Third, I model consumers' utility from adopting and using mobile phones. Almost all phones in Rwanda were basic, prepaid mobile phones.[5] 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.[6] 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.[7] 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 with hypothetical questions to estimate switching costs and idiosyncratic preferences.

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

I simulate the industry from January 2005 through December 2008 (a slightly shorter horizon under which the relevant network of consumers is spanned by the data). I simulate the baseline policy (which can be thought of as lying between a monopoly and duopoly, as Operator B was poorly run). I also simulate a counterfactual where the government grants Operator C a license in January 2005 under an interconnection rate of \$0.11/min. The entrant selects its price path, the incumbent selects its price path and rollout plan, and then consumers decide when to adopt and how to use phones. I find:

Adding a competitor could have lowered prices by 30%–50% and *increased* incentives to invest in rural towers. This policy would have increased the net welfare provided by the mobile phone system by up to 38% (\$112 m in a low equilibrium or \$153 m in a high equilibrium, over 4 years), 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.

I find that tower investments induce limited spillovers across networks: When the network is split, the incumbent still internalizes 95%–99% of incremental profits from building rural towers (holding fixed operator choices), but investing attracts consumers from the other operator. Because of this busines stealing effect, the incumbent can face a higher return from investment when it faces an additional competitor even though it earns lower total profits. The business stealing effect accounts for 80%–88% of the incumbent's profit from the investment, coming from semiurban consumers who partially value rural coverage.

Overall outcomes depend on the competition policy used. Although the return on investment (ROI) can be higher under competition, it declines as the networks are made more compatible through lower interconnection fees. Building the rural towers is still profitable under the entire range of interconnection fees. Lower interconnection fees also lead to lower prices and higher welfare. A policy to reduce switching costs (number portability) increases the level of competition. Delaying entry results in smaller effects during this time period.

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

[6] 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.

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

Altogether, this article introduces an approach that could be applied by a regulator planning policy scenarios for a dominant 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 could 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.

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 consumers in this unobserved (or "dark") portion of the network, and report results through a shorter time horizon before these nodes would have adopted (through December 2008 rather than when my data ends in May 2009).

□ **Related literature.** This article builds on the demand model for a good with direct network effects estimated in Björkegren (2019), which has parallels to Ryan and Tucker (2012)'s model of videoconferencing adoption. Most empirical work on direct network effects simply measures their extent; see, for example, Saloner and Shepard (1995), Goolsbee and Klenow (2002), and Tucker (2008). Weiergraeber (2021) estimates demand for mobile phone operators in the United States, using data on market shares and churn rates that vary by segment and region. That article shows that demand estimates can be misleading if either switching costs or network effects are omitted.[8] I also find that common simplifications can lead to misleading estimates in direct network industries: In simulations in the Online Appendix, 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 the other side of the market. These include a variety of platforms and formats (Ohashi, 2003; Gowrisankaran, Rysman, and Park, 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, Fong, and Fradkin (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.[9] Because I can use regulator cost data, I skip estimating costs from dynamic decisions (Bajari, Benkard, and Levin, 2007; Pakes et al., 2008).

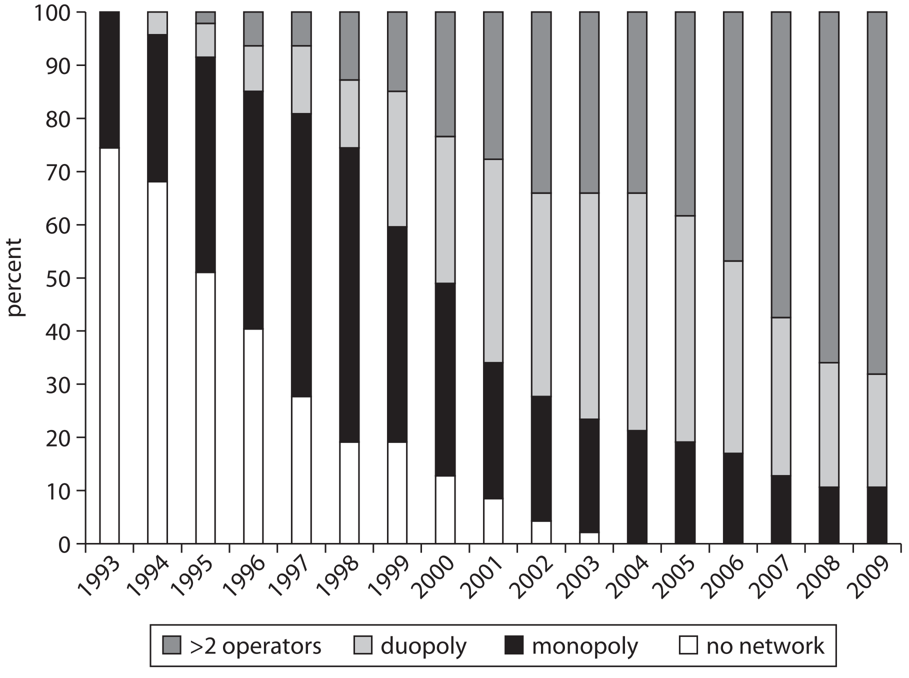
Goettler and Gordon (2011) and Igami (2017) together suggest the effect of competition on innovation can vary based on industry primitives. My setting differs in that operators face network effects and earn revenue from ongoing service fees, so do not compete with previous vintages of product.

[8] That article studies mature networks where network effects are in market shares: consumers prefer to use larger networks in part because in-network prices are lower. In my model of a growing network, network effects are primarily in adoption and firms are not allowed to charge different prices for off-network calls.

[9] The model has both direct network effects in adoption (my utility depends on whether my particular contacts adopt) as well as scale 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).

FIGURE 1

MOBILE TELECOM COMPETITION IN SUB-SAHARAN AFRICA



Note: Percent of countries with different industry structures. Source: Williams, Mark; Mayer, Rebecca; Minges, Michael. 2011. Africa's ICT Infrastructure: Building on the Mobile Revolution. ©World Bank. License: CC BY 3.0 IGO.

My approach complements comparisons between countries that set different telecom policies. Genakos, Valletti, and Verboven (2018) and Faccio and Zingales (2021) 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.[10]

2. Context

□ **Developing country phone systems.** Developing country regulators typically started mobile phone industries by granting temporary monopolies, and then gradually licensing 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.[11] 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 pre-announcing entry dates or glide paths for interconnection, though there are occasional "surprises" (unannounced, sudden policy changes). Later entrants typically charged lower prices and served densely populated areas, which are more lucrative.

[10] For reviews, see Cambini and Jiang (2009) and Manganelli and Nicita (2020).

[11] 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 for spectrum. See Online 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%	

Note: 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.[12]

□ **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.[13] 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)).

The market structure of the industry changed several times:

(1) 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.[14] After several changes in ownership, it reached a maximum of 20% market share for a brief period after the end of my data.
(2) In 2008, the Rwandan regulator asked for bids and rollout plans for a third license. It granted the license to a third, multinational operator (Operator C), which entered at the end of 2009, and required the previous operators to renew their licenses. A consultant recommended lowering interconnection rates based on cost data (PwC, 2011).
(3) In 2011, Operator B's license was revoked for failure to meet obligations, and its assets and license were absorbed into a new entrant, Operator D.
(4) 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 article 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.

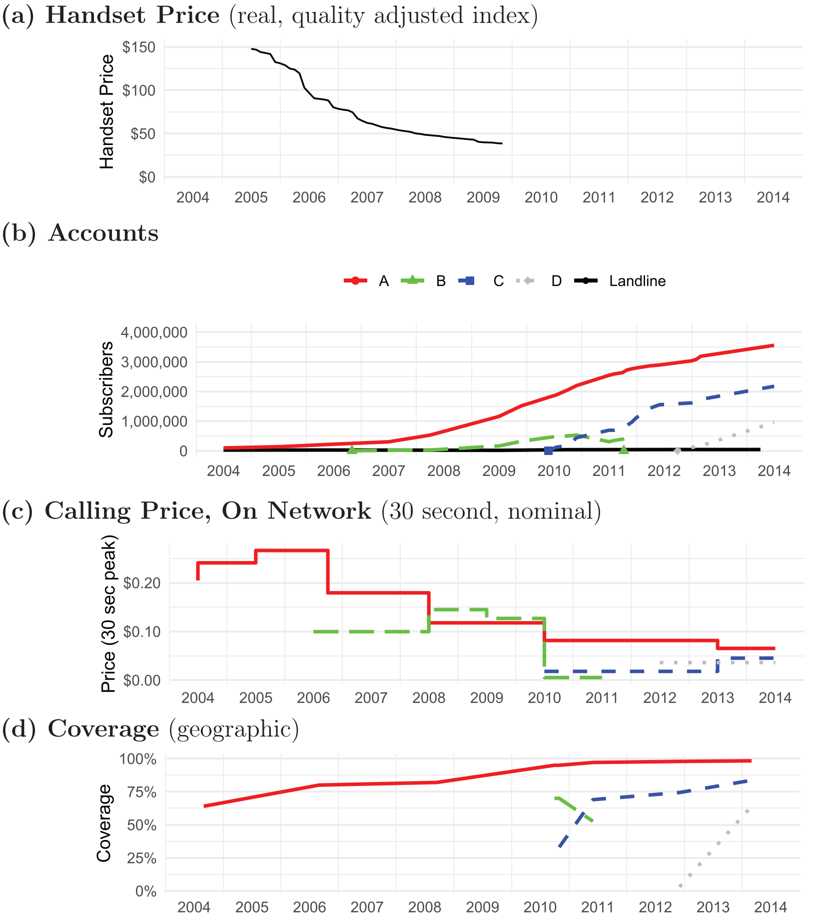
[12] Additionally, most interconnection models are designed for mature developed country networks, and so do not account for network effects in adoption.

[13] These are enforced: When Operator B failed to comply with its rollout plan, it was fined and its license was ultimately revoked. The relevant law allowed the regulator to levy a fine each month as much as 15% of Operator B's revenue as of 2007.

[14] It was part of the former state landline company, but was purchased by an American satellite entrepreneur who was disconnected from realities on the ground (IGIHE.com, 2011). 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."

FIGURE 2

DEVELOPMENT OF TELECOMMUNICATIONS IN RWANDA
[Color figure can be viewed at wileyonlinelibrary.com]



Note: Handset prices reported during the years I have data on prices and quantities, compiled from operator records, operator website, and records of an independent handset shop (Björkegren, 2019). Other measures sourced from archived operator websites and regulator annual reports (RURA).

□ **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.[15] 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 was not available at this point.

3. Data

■ This project uses several data sources:[16]

Call detail records: As a byproduct of providing service, mobile phone operators record data about each transaction, called Call Detail Records (CDRs). This project uses 4.5 years of

[15] In Rwanda, most appear to be purchased from independent sellers: Operator handset sales records account for only 10% of total handsets activated during the period of my data.

[16] For more information, see Online Appendices S1– S3.

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: Research ICT Africa 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.

anonymous call records from Operator A, which held above 88% of the market during this period. This data include nearly every call between the operator's subscribers, numbering approximately 400,000 in January 2005 (time $t = 0$) and growing to 1.5 million in May 2009 ($t = T$). It does not include the small number of calls to subscribers of Operator B. For each transaction, the data report: anonymous identifiers for sender and receiver, corresponding to the phone number and handset, time stamps, the location of the cell towers used, and call duration.[17] 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: I create geographic 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).

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.

4. Model

■ The incumbent arrives in month $t = 0$ (January 2005) with an initial set of subscribers and towers. The government announces policy: when the entrant may enter, and interconnection fee f. Given these, each firm F chooses calling prices ($\mathbf{p}^F$) and tower rollout ($\mathbf{z}^F$), sequentially. Then, each consumer i decides which month to adopt a phone ($x_i \in \{1, \ldots \bar{T}\}$), which operator to use (a_{it}), and how many seconds to call each contact ($d_{ijt} \geq 0$). I consider Rwanda's handset market as perfectly competitive, with exogenous prices unaffected by the market for service.

Although the data end at time $t = T$ (May 2009), I avoid extrapolation issues by having firms optimize through time horizon $t = \tilde{T}$, which is typically shorter (December 2008 for the

[17] Data are missing for May 2005, February 2009, and part of March 2009.

primary analysis). I report outcomes under different horizons $\tilde{T}$. To allow consumers to delay adoption, consumers have beliefs about how the market will continue after this horizon (through $t = \bar{T} = T + 36$: May 2012).[18]

□ **Government.** In month $t = 0$, the government announces its policy through $t = \bar{T}$: either it will not license an additional competitor ("baseline"), or will additionally license Operator C ("competition") with interconnection fee f, which affects the level 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). I assume that the government asks the entrant to move first, and restricts firms to charge subscribers the same price for calls placed within the same network (on-net) as to the other network (off-net).[19]

The government earns revenue from taxes on adoption ($\tau_{it}^{\text{handset}}$) and usage ($\tau_{it}^{\text{usage}}$); these rates are held fixed and their path is announced in advance.[20] I do not take a stand on whether the government maximizes tax revenue, welfare, or another objective.

□ **Firms.** The entrant ($F = E$), and then incumbent ($F = I$) select a tower rollout plan $\mathbf{z}^F$ and a path of calling prices $\mathbf{p}^F = (p_t^F)_{t=0}^{\tilde{T}}$. Their profits through horizon $t = \tilde{T}$ depend on consumer adoption and usage:

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

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

A rollout plan, $\mathbf{z} = \{(t_z^{\text{tower}}, lat_z, long_z)\}$, is defined by tower build dates and geographical coordinates. I index potential rollout plans so that $\mathbf{z}_{(r)}$ represents a plan to build all urban towers but only the proportion r of rural towers covering the highest populations, with $\mathbf{z}_{(100\%)}$ representing the baseline rollout.[21] The entrant builds only urban towers ($\mathbf{z}^E = \mathbf{z}_{(0\%)}$), following its parent company's articulated strategy in Africa (and later initial plan in Rwanda).[22] The incumbent builds urban towers and also selects the proportion of rural towers r to build ($\mathbf{z}^I \in \{\mathbf{z}_{(100\%)}, \mathbf{z}_{(50\%)}\}$; see Figure 3).[23]

Firms may select calling prices as a multiple of the incumbent's baseline price path: $\mathbf{p}^F \in \psi \cdot \mathbf{p}^{\text{base}}$, for a choice from the grid $\psi \in \{0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1\}$ and $\mathbf{p}^{\text{base}} = (p_t^{\text{base}})_{t=0}^{\tilde{T}}$.[24]

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[18] In practice, these beliefs about $t > \tilde{T}$ have little influence on outcomes through $\tilde{T}$.

[19] This order of play is selected to more closely match what happened in Rwanda, where the entrant submitted its bid for the new phase of competition first. Although 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.

[20] The government earns tax revenue:

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

where S_t is the set of individuals with phones in month t, x_i represents i's adoption date, a_{it} i's operator, $p_t^{a_{it}}$ is the calling price, G_i represents the contacts of i, and $\mathbb{E} d_{ij}(\ldots)$ 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.

[21] Rankings determined based on population within a 10 km radius.

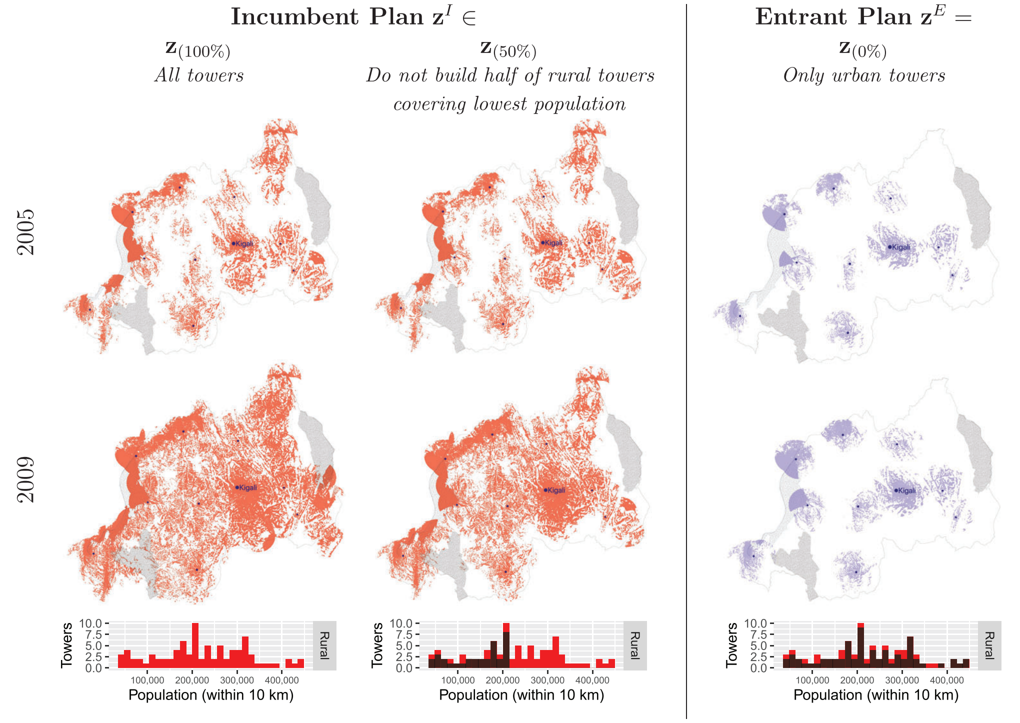
[22] Operator C's global Annual Report in 2010 said: "There is scope for further coverage growth in our African markets, but urban centers currently represent the significant majority of the addressable population."

[23] The Online Appendix considers a wider set of options.

[24] This baseline price path is shown in Figure 2.

FIGURE 3

ROLLOUT PLANS
[Color figure can be viewed at wileyonlinelibrary.com]



Note: Shows the coverage plans that operators may choose from. Starting from its set of towers in 2005, the incumbent may build all additional 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 with dots; Lake Kivu shown with ripples.

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:

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

where S_t is the set of individuals with phones in month t, G_i represents the contacts of i, and $\mathbb{E}d_{ij}(\dots)$ represents the expected seconds that individual i calls j.[25]

Firm F incurs costs:

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

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

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. $ic^{direction}_{L_i,onnet_{ij}}$ is the incremental cost of sending or receiving an additional second for $direction \in \{\text{in, out}\}$. Costs vary by whether the two parties are on the same network, and between subscriber primary location ($L_i \in \{\text{urban, rural}\}$).[26]

I assume that the decisions of the poorly run competitor (Operator B) are held fixed.

□ **Consumers.** Given the government's policy and firm decisions $(\mathbf{z}^F, \mathbf{p}^F)_F$, each consumer i decides when to adopt a phone (x_i), and each month after adopting which operator to use ($a_{it} \in \{I, E\}$) and how many seconds to call each contact ($d_{ijt} \geq 0$).[27]

This model extends the demand model 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.[28] I observe the communication graph G^I_T, where a directed link $ij \in G^I_T$ indicates that i has called j by the end of the data (period T) while both subscribed to the incumbent.[29] Define $G_i = \{j | ij \in G^I_T\}$ 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.) I do not observe subscribers of the poorly run competitor (Operator B), and so assume they do not change their decisions in counterfactuals; this will tend to attenuate the effects of competition.

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, for each contact he chooses a duration $d_{ijt} \geq 0$ for that month, earning utility:

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

where 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:

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

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

[27] I do not explicitly model utility from text messages, missed calls, international calls, and calls from payphones. Any value these omissions provide is captured in a residual in the adoption decision. 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 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. If the government policy does not allow the entry of the additional competitor (E), consumers have no choice of operators but the incumbent ($a_{it} = I$).

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

[29] G^I_T 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 $S^I_T \subseteq N$. This will miss any links between subscribers where there is a latent desire to communicate but no call has been placed by T ($G^I_T \subseteq \bar{G}^I_T$).

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:

$$c_{ijt} = p_t^{a_{it}} + \beta_{\text{coverage}}\phi_{it}(\mathbf{z}^{a_{it}})\phi_{jt}(\mathbf{z}^{a_{jt}})$$

The second term represents the hassle cost when the caller or receiver have imperfect coverage, where $\phi_{it}(\mathbf{z}) \in [0, 1]$ represents the average coverage available at individual i's most used locations, under rollout plan $\mathbf{z}$. i's locations are derived from clustering the locations of towers that i uses a phone, using a method analogous to triangulation in Björkegren (2019).

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:

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

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 $\epsilon_{ijt} \leq \underline{\epsilon}_{ijt} := \frac{\alpha}{1-\beta_{\text{cost}}(p_t^{a_{it}}+\beta_{\text{coverage}}\phi_{it}(\mathbf{z}^{a_{it}})\phi_{jt}(\mathbf{z}^{a_{jt}}))}$.

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

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

and provide expected utility:

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

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

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

where x_j represents j's adoption time and s the cost of switching operators.[30] However, at the point of adoption, i anticipates that having a phone in month t will provide utility:

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

where an individual's type (η_i^I, η_i^E) 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 $x_i \in \{1, \ldots \bar{T}\}$, based on the actual paths of contact adoptions ($\boldsymbol{x}_{G_i}$), call prices ($\mathbf{p}_x$), and rollout ($\mathbf{z}_x$). He knows the current handset price (p_t^{handset}, inclusive of any tax), and has beliefs about future handset prices and contact operator choices.

[30] This model assumes that the utility of a call accrues to the person who pays for it (the caller), rather than model how call utility is split between caller and receiver. Björkegren (2019) also considers the possibility that consumers additionally earn the equivalent utility from the calls they receive (which are free); although market outcomes are not very different for the counterfactuals in that article, this double counts call utility relative to the utility implied by the adoption decision.

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:

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

under deterministic beliefs that in period $x > t$, the handset price will be $\mathbb{E}_t p_x^{\text{handset}}$, 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:

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

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:

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

which is net of calling, hassle, and handset costs.[31]

□ Expectations.

Equilibrium index. For each profile of the firms' strategies, there may be multiple adoption subgame equilibria among consumers; this gives rise to multiple equilibria at the industry level.

I focus on families of consumer adoption equilibria $\underline{e}^A$ and $\bar{e}^A$ that are indexed along two dimensions. First, equilibria are indexed by the speed of adoption, focusing on the earliest ($\bar{e}$) or latest ($\underline{e}$) adoption equilibria. Second, equilibria are indexed by whether operator choices favor the incumbent ($A = I$) or entrant ($A = E$) (similar to Jia (2008)). Along these dimensions, adoption equilibria form a lattice.[32]

I restrict consideration to industry equilibria in which firms anticipate a degree of continuity in the subgame equilibria played by consumers. If consumers play an equilibrium of index e in the subgame resulting from firm actions ($\mathbf{p}^I, \mathbf{p}^E, \mathbf{z}^I, \mathbf{z}^E$), firms believe that they will also play an equilibrium of index e in the subgame resulting from alternate actions ($\tilde{\mathbf{p}}^I, \tilde{\mathbf{p}}^E, \tilde{\mathbf{z}}^I, \tilde{\mathbf{z}}^E$).[33]

Additional beliefs. 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

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

[32] Adoption equilibria form a lattice in the two dimensions along which equilibria are indexed, adoption ($\boldsymbol{x}$) and, conditional on adoption, operator choice ($\mathbf{a}$). $\boldsymbol{x}$ has a lattice structure because $\mathbb{E}_t U_i^{\mathbf{a}_i,x_i}(\mathbf{p}, \mathbf{z}, \boldsymbol{x}_{G_i}, \hat{\mathbf{a}}_{G_i})$ 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 $\phi_{jt}(\mathbf{z}^{a_{jt}})$. Likewise, conditional on $\boldsymbol{x}$, $\mathbf{a}$ has a lattice structure because coverage choices are complementary. As long as the coverage and prices provided by the two firms is ordered (one with higher prices and weakly greater coverage for all consumers), when a contact switches firms, that will weakly increase a consumer's incentives to be on the same network. As a result, $\mathbb{E}_t U_i^{\mathbf{a}_i,x_i}(\mathbf{p}, \mathbf{z}, \boldsymbol{x}_{G_i}, \mathbf{a}_{G_i})$ is supermodular in a_i and a_j, conditional on $\boldsymbol{x}_{G_i}$.

[33] Note that this industry equilibrium that restricts to the slowest or fastest adoption in every adoption subgame may not yield the slowest or fastest overall adoption. It may be possible to obtain more extreme adoption in the industry equilibrium if firms have 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 (and spur faster adoption) than if they believed that consumers would adopt according to similarly optimistic equilibria in each subgame (and likewise for operator favor).

this period: $\mathbb{E}_t p_x^{\text{handset}} = \omega^{x-t} p_t^{\text{handset}}$ for $\omega = (\frac{p_T^{\text{handset}}}{p_0^{\text{handset}}})^{\frac{1}{T}}$. If an individual forecasts differently, the error will be captured in his type (η_i^I, η_i^E).[34]

Prior to purchasing a handset, i believes that each contact j will use the operator $\hat{\mathbf{a}}_j(\mathbf{p}, \mathbf{z})$ that is optimal given prices and coverage at j's location, for calls to the median individual at final month of data T.[35]

□ **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 $(\mathbf{p}^I, \mathbf{p}^E, \mathbf{z}^I, \mathbf{z}^E, \mathbf{x}, \mathbf{a}, \mathbf{d})$ such that:

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

$$\begin{aligned}\mathbf{p}^E = \arg\max_{\mathbf{p}^E} \pi_E^{\tilde{T}} \Bigg(& \mathbf{p}^{I*}(\mathbf{p}^E), \mathbf{p}^E, \mathbf{z}^{I*}(\mathbf{p}^E), \mathbf{z}^E, \\ & \mathbf{x}^*(\mathbf{p}^{I*}(\mathbf{p}^E), \mathbf{p}^E, \mathbf{z}^{I*}(\mathbf{p}^E), \mathbf{z}^E, \boldsymbol{\eta}, e), \\ & \mathbf{a}^*(\mathbf{p}^{I*}(\mathbf{p}^E), \mathbf{p}^E, \mathbf{z}^{I*}(\mathbf{p}^E), \mathbf{z}^E, \boldsymbol{\eta}, e), \\ & \mathbf{d}^*(\mathbf{p}^{I*}(\mathbf{p}^E), \mathbf{p}^E, \mathbf{z}^{I*}(\mathbf{p}^E), \mathbf{z}^E, \boldsymbol{\eta}, e), f \Bigg)\end{aligned}$$

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

$$\begin{aligned}\mathbf{p}^{I*}(\mathbf{p}^E), \mathbf{z}^{I*}(\mathbf{p}^E) = \arg\max_{\mathbf{p}^I, \mathbf{z}^I} \pi_I^{\tilde{T}} \Bigg(& \mathbf{p}^I, \mathbf{p}^E, \mathbf{z}^I, \mathbf{z}^E, \\ & \mathbf{x}^*(\mathbf{p}^I, \mathbf{p}^E, \mathbf{z}^I, \mathbf{z}^E, \boldsymbol{\eta}, e), \\ & \mathbf{a}^*(\mathbf{p}^I, \mathbf{p}^E, \mathbf{z}^I, \mathbf{z}^E, \boldsymbol{\eta}, e), \\ & \mathbf{d}^*(\mathbf{p}^I, \mathbf{p}^E, \mathbf{z}^I, \mathbf{z}^E, \boldsymbol{\eta}, e), f \Bigg)\end{aligned}$$

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

- Each initial adopter $i \in S_0$ selects operator sequence $\mathbf{a}_i \in \{I, E\}^{\tilde{T}}$ 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 $x_i \in \{1, \ldots, \bar{T}\}$ optimally, believing j will use predicted operator $\hat{\mathbf{a}}_j(\mathbf{p}, \mathbf{z})$
  - operator sequence $\mathbf{a}_i \in \{I, E\}^{\tilde{T}-x_i}$ optimally, believing j uses operators $\mathbf{a}_j$
- Each month t after adopting, i calls contact j for $d_{ijt} = \mathbb{E} d_{ij}(\mathbf{p}_t, \mathbf{z}_t, \mathbf{a})$ seconds

[34] 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.

[35] That is, $\hat{\mathbf{a}}_j(\mathbf{p}, \mathbf{z}) = \arg\min_a [p_T^a + \beta_{\text{coverage}} \phi_{jT}(\mathbf{z}^a) \phi_{mT}(\mathbf{z}^{a_m})]$, where m represents the individual with median coverage, who selects his operator analogously: $a_m = \hat{\mathbf{a}}_m(\mathbf{p}, \mathbf{z})$. Consumers predict based on operator offerings in the final month of data T to capture a belief about long run quality. In the Online Appendix, I also consider approximate equilibria where consumers correctly anticipate contacts' operator choices; results are similar.

□ **Discussion.**

Uniqueness. I have not empirically found instances of multiple equilibria in simulations after restricting consideration to consumer adoption equilibria of index e, but I have not proved uniqueness of the equilibrium including firms' decisions.

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 the end of the data T, nor links between individuals ij that were latent and would have 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. I compute counterfactuals that lie within the range of conditions observed in my data (through $t = T$) by reporting simulation results for shorter horizons $\tilde{T} \leq T$ during which counterfactual adoption conditions would be no more favorable.[36] Main results use a horizon ($\tilde{T}$ =December 2008) computed using the structural model and a representative survey covering part of the dark network (RIA, 2012); the Online Appendix reports a conservative horizon limited to the observed variation in calling prices.[37]

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 Online 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.[38]

5. Estimation

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

Switching costs (s) and the distribution of idiosyncratic operator preferences ($\{\eta_i^I - \eta_i^E\}$) 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:

[36] Counterfactuals that lower prices speed up adoption, which is akin to fast forwarding a film; presenting outcomes for a limited time horizon is akin to pausing the film before it runs out of tape.

[37] For more details and definitions of these horizons, see Online Appendix S5.

[38] See Online 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	$m(\{\eta_i^I - \eta_i^E\})$	\$2.45	Hypothetical switching exercises
. . . SD	$\sigma(\{\eta_i^I - \eta_i^E\})$	\$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)

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

(1) **Consumer choices**
For a grid of price choices $(\mathbf{p}^I, \mathbf{p}^E)$ and rollouts $\mathbf{z}^I$, 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 $\hat{\mathbf{a}}_{-i}(\mathbf{p}, \mathbf{z})$, 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 $\mathbf{p}^I(\mathbf{p}^E)$ and $\mathbf{z}^I(\mathbf{p}^E)$ to maximize profits through $\tilde{T}$, anticipating consumer choices in equilibrium e.

(3) **Entrant choices**
The entrant selects $\mathbf{p}^E$ 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.[39] 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 $\Delta\eta_i \overset{iid}{\sim} N[m(\eta_i^I - \eta_i^E), \sigma(\eta_i^I - \eta_i^E)]$, and compute $[\underline{\eta}_i^E, \bar{\eta}_i^E] = [\underline{\eta}_i^I - \Delta\eta_i, \bar{\eta}_i^I - \Delta\eta_i]$. I present results from a single random draw and assess the effect of the random draw in the Online Appendix.

7. The effects of competition

■ I consider counterfactuals that add an additional competitor, investigate investment effects, and then consider different policies (interconnection rates, number portability, and delay). I report outcomes on prices, towers built, returns on investment (ROI), consumer surplus, profits, government revenue, and total welfare. In the main text, I focus on incumbent-favoring equilibria and refer to the lowest equilibrium outcomes $(\underline{e}^I)$ in text (and place the highest equilibrium $\bar{e}^I$ outcomes in parentheses, or omit if identical). I present results from January 2005 to December

[39] See Online Appendix S6 for pseudocode.

TABLE 4 Market Outcomes under Competition

	Outcomes (January 2005-December 2008)						
	Call Prices		Rollout Plan	C.	Profit		Gov.
	$\frac{\mathbf{p}^I}{\mathbf{p}^{base}}$	$\frac{\mathbf{p}^E}{\mathbf{p}^{base}}$	$\mathbf{z}^I$	Surplus $m	Incumbent $m	Entrant $m	Revenue $m
Baseline scenario	1.00, 1.00	-	$\mathbf{z}_{(100\%)}$	168, 194	108, 126	0, 0	58, 66
Additional competitor	0.70, 0.60	0.60, 0.50	$\mathbf{z}_{(100\%)}$	281, 365	98, 104	5, 2	62, 68

Note: Each cell reports the low and high incumbent-favoring equilibrium. Competitor is introduced under interconnection $f = \$0.11$/min starting at $t = 0$ (1/2005). Profits omit fixed costs of operation and license fees. Utility and revenue reported in 2005 US 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.

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).[40]

I find:

□ **Competition lowers prices and can increase incentives to invest.** I compare outcomes under the baseline to a scenario where an additional competitor is added with a focal interconnection rate of $f = \$0.11$/min (Table 4 rows 1 and 2; each cell reports the low and high equilibrium). Under this policy, the incumbent would reduce prices to 70% (60%) of the baseline price path, and the entrant to 60% (50%). The incumbent would have still built all rural towers.

This lowers profits for the incumbent but has a large impact on consumer surplus: lower prices bring more users to the network, which also increases the value each user gets from the network. Altogether, the total social 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.[41] Additionally, the welfare in the low equilibrium with an additional competitor exceeds that in the high equilibrium at baseline.

Incentives to invest are driven by business stealing. To more finely investigate investment, I evaluate the effects of building rural towers in Table 5. Fixing the above competitive prices, I compute the adoption equilibrium that would result if the incumbent neglected to build the 50% of rural towers in the lowest population areas ($\mathbf{z}^I = \mathbf{z}_{(50\%)}$). From that adoption equilibrium, I compute the new adoption equilibrium that would result if the incumbent instead built the full set of towers ($\mathbf{z}^I = \mathbf{z}_{(100\%)}$). I do this in two stages. First, I hold fixed each consumer's choice of operator, but allow consumers to change adoption dates and usage. Then, I allow consumers full choice over usage, adoption, and operator.

Table 5 rows 1 and 2 report the overall effect on the incumbent's incremental profits and ROI from building these rural towers, in the baseline scenario and when there is an additional competitor. Under the baseline scenario, the incumbent earns positive profits and an ROI of 0.98 (1.00) from building these towers (first row), but it earns *more* from building these towers when it faces an additional competitor: its incremental profits are higher, and its ROI increases to

[40] 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 Online Appendix.

[41] Over the horizon from 2005 to 2008, in the baseline scenario, the incumbent provided a social surplus of $334 m ($386 m), 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 $8 m (4% of the total welfare generated), or the promise of an acquisition or additional future profits as the network grows.

TABLE 5 Return on Tower Investment

	Equilibrium Call Prices		Effect of Incumbent Building Low Population Towers			
			ΔProfit		ROI	
	$\frac{p^I}{p^{base}}$	$\frac{p^E}{p^{base}}$	Incumbent $m	Entrant $m	Incumbent	Social
Baseline scenario	1.00, 1.00	-	1.27, 1.23	-	0.98, 1.00	6.64, 6.49
Additional competitor	0.70, 0.60	0.60, 0.50	1.99, 1.87	−1.27, −1.25	1.40, 1.26	7.74, 7.96
…fixing operator			0.39, 0.22	0.022, 0.002	0.43, 0.25	6.89, 6.92
…add'l effect of operator choice			1.60, 1.65	−1.30, −1.26	-	-

Note: Each cell reports results in the low and high incumbent-favoring equilibrium. Effect cells report the difference in outcomes between the adoption equilibrium that results when the lowest 50% population rural towers are built, and the one where the incumbent is constrained to not build them. 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. 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 because the cost of the towers has already been accounted for. Utility and revenue reported in 2005 US 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.

1.40 (1.26; second row). When the incumbent builds these towers, it decreases the profits of the entrant. Under either market structure, private ROI is far lower than the social ROI of as much as 7.74 (7.96), suggesting this market may see underinvestment.

To better understand this result I decompose the two stages of consumer optimization. If operator choices were held fixed (Table 5 row 3), the towers would earn the incumbent only a small amount of profits and a lower ROI of 0.43 (0.25). The entrant benefits from the incumbent's tower construction in two ways:

(1) The entrant's subscribers call contacts in the incumbent's network more (due to better reception, and because that causes some of the incumbent's subscribers to adopt earlier, which causes others to adopt earlier). These additional calls between the two networks (entrant's off-net calls) account for 89% (98%) of the additional revenue that accrues to the entrant. These positive externalities are partially internalized: 56% (76%) is paid back to the incumbent through interconnection fees.
(2) Adoption spillovers lead to additional usage inside the entrant's network as well. 11% (2%) of the revenue results from positive externalities inside the entrant's network (entrant on-net calls). Interconnection fees are incurred only at the boundaries of the two networks, and so do not adjust for these positive externalities.[42]

Altogether, the benefits accruing to the entrant's network are small: The incumbent still captures 95% (99%) of the profits from investing, when consumers' choices of operator are held fixed.

When consumers are able to adjust all choices, including the choice of operator, urban consumers who spend a fraction of their time in rural areas switch networks to the incumbent to take advantage of its improved coverage (Table 5 row 4).[43] This additional business stealing effect dominates: It accounts for 80% (88%) of the profit the incumbent earns from the investment, dwarfing the size of the network effects that the incumbent does not internalize.

[42] 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.

[43] For a breakdown of switchers, see Figure A1.

Although it is computationally costly to compute full equilibria for a larger set of rollout cutoffs, ROI for tower construction is weakly larger under the focal competition policy for an expanded set of rollout plans (incumbent selecting $\mathbf{z}^I \in \{\mathbf{z}_{(100\%)}, \mathbf{z}_{(75\%)}, \mathbf{z}_{(50\%)}, \mathbf{z}_{(25\%)}, \mathbf{z}_{(0\%)}\}$ versus entrant $\mathbf{z}^E = \mathbf{z}_{(0\%)}$) when I hold fixed equilibrium prices from the full rollout ($\mathbf{z}_{(100\%)}$) and consider unilateral incentives to deviate. This is shown in Online Appendix S8. 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.

Altogether, although competition reduces the incumbent's total profit, it can *increase* the returns to investment. An investment in towers improves coverage, which retains customers who otherwise would switch when given the option. However, the net effect of competition on investment will generally depend on the relative size of network and business stealing effects; and, as we will see next, on the interconnection policy.

□ **Compatibility introduces a tradeoff between prices and incentives to invest.** Next, I consider selecting different interconnection rate policies. 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).

The focal interconnection rate of $f = \$0.11$ (shown in a dotted line) is higher than consultant recommendations at that time ($f = \$0.07$ (RURA, 2006) or \$0.09 (PwC, 2011)), or suggestions to make interconnection free for firms ($f = \$0$: "zero rating" or "bill and keep," to which the U.S. is transitioning (FCC, 2019)).

The interconnection rate acts like a tax on off-network calls; as the interconnection fee is lowered, firms lower their prices (top panel). However, there is a tradeoff: As the interconnection rate is lowered, the ROI of building low population rural towers declines (middle panel). This is because lower prices lead to lower revenues, and the incumbent collects less interconnection payments relative to the spillover benefits it provides to the other network. The ROI is always above zero so it would still have been profitable to build the towers. Finally, as the interconnection rate is lowered, welfare increases and incumbent profits decline (bottom panel).

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). That would mute the effect of competition on prices (80%–90% of baseline scenario) and welfare.[44] This anti-competitive effect is reminiscent of many 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).

□ **Additional policies.** Table 6 compares outcomes for the baseline and focal competition policies against two additional policies (holding fixed the incumbent's investment, $\mathbf{z}^I = \mathbf{z}_{(100\%)}$) :

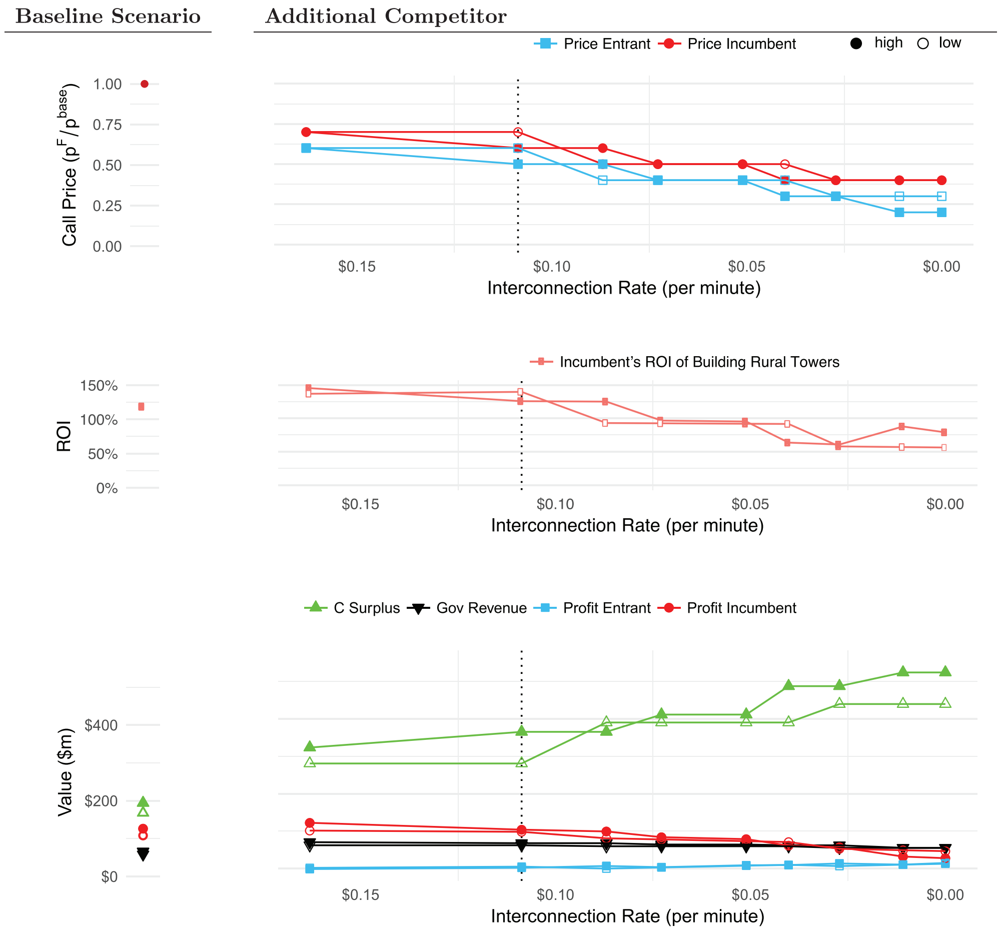
Number portability. Policies that allow consumers to port their phone numbers between operators have been planned or implemented by 40% of developing country regulators (GSMA, 2013).[45] My consumer survey suggests that number portability would lower users' hassle cost of switching operators from \$36.09 to \$18.51. Number portability lowers prices, incumbent profits, and

[44] I allow the incumbent to select the interconnection rate on a grid from \$0.00 to \$0.43. Note that results could differ if firms were allowed to set separate prices for on- and off-net calls.

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

FIGURE 4

MARKET OUTCOMES AS FUNCTION OF INTERCONNECTION RATE
[Color figure can be viewed at wileyonlinelibrary.com]



Note: 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. All equilibria shown have entrant moving first, and consumers favoring incumbent. Outcomes reported in 2005 US 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.

increases social welfare in the lower equilibrium but has muted effects in the upper equilibrium (Table 6 row 3).[46] Given the choice, the incumbent would elect to maintain high switching costs.

Delayed entry. If entry of the competitor is delayed from January 2005 to 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 6 row 4).

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

TABLE 6 Additional Competition Policies

	Switch. Cost s $	Call Prices $\frac{\mathbf{p}^I}{\mathbf{p}^{\text{base}}}$	$\frac{\mathbf{p}^E}{\mathbf{p}^{\text{base}}}$	C. Surplus $m	Profit Incumbent $m	Entrant $m	Gov. Revenue $m
		Outcomes (January 2005–December 2008)					
Baseline scenario	-	1.00, 1.00	-	168, 194	108, 126	0, 0	58, 68
Additional competitor	36	0.70, 0.60	0.60, 0.50	281, 365	98, 104	5, 2	62, 68
Number portability	19	0.50, 0.60	0.50, 0.50	384, 366	88, 101	-1, 5	61, 68
Delayed entry (7/2008)	36	0.70, 0.70	0.40, 0.30	259, 284	98, 109	2, 2	59, 65

Note: Each row presents the outcomes under a given policy, in the low and high incumbent-favoring equilibria. All competitive results are under $f = \$0.11$/min; unless denoted, entry is 1/2005. Profits omit fixed costs of operation and license fees. Utility and revenue reported in 2005 US 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.

□ **Robustness.** I assess several alternate specifications in the Online Appendix (S9–S14).

Results are similar under different time horizons ($\tilde{T}$). A shorter time horizon ($\tilde{T}$ =December 2005) yields analogous price reductions and welfare increases.[47] Under an extended horizon ($\tilde{T} = T + 36$), where upon reaching T that final month repeats 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 $[\underline{\eta}_i^E, \bar{\eta}_i^E]$, and under entrant-favoring equilibria. If at the time of adoption, consumers correctly 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 notion of equilibrium. If the incumbent moves before the entrant, or the two firms move simultaneously, results are less stable, but are similar for prices and welfare. The ROI effects are less stable, but there still exist competition policies that would increase ROI for at least one adoption equilibria.

When modeling demand in a network industry, one may be tempted to model a simplified network (due to lack of data or for ease of computation), but I find that such simplifications can lead to large errors. 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%.

Welfare effects are similar to the focal competition policy if the government does not grant a license to the entrant, but instead forces the incumbent to lower its price to the later competitive level (in the monopoly model). This should be viewed as a check on the model rather than a policy recommendation, as there are downsides to price regulation that I do not model.

8. Conclusion

■ This article 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 entry of an additional firm in the Rwandan mobile phone industry has a large scope to affect welfare. Policies to increase competition have mixed effects on incentives to invest: Competing firms must split the revenue generated by an investment, but may be motivated to increase quality to steal business. It is an open question whether these results would be

[47] This horizon does not cover the construction of many rural towers, so is not well suited to answering questions about investment.

similar for mobile internet, which still has low penetration in much of sub-Saharan Africa, and for other goods with direct network effects around the world. Although I focus on investments in rural towers, operators may consider multiple types of investments which would be differentially affected by competition. Relative to the baseline situation, adding an additional competitor encourages investments for business stealing and discourages investments with dispersed network externalities that are difficult to appropriate. Thus, competition policy is likely to affect the nature of network products provided by the market, and may lead to welfare implications more profound than documented here.

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. In comparison, Weiergraeber (2021) estimates an average cost of switching between US mobile phone operators between \$47 and \$178; 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 $m(\eta_i^I - \eta_i^E) = \$2.45$ (\$0.01 per month), and standard deviation $\sigma(\eta_i^I - \eta_i^E) = \$6.72$. 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.[48] 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. Online Appendix S4 assesses the extent to which the model matches behavior observed later in Rwanda, and in countries that were competitive at this time.

□ **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.[49] 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.[50] 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.[51] 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 capacity and 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 because remote towers may have few users.

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.[52]

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48 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.

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

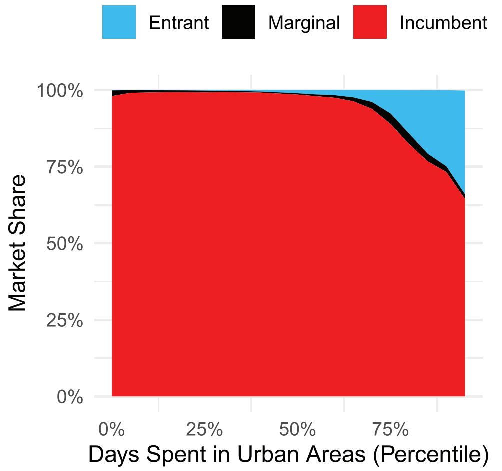
50 Although marginal costs are in many cases zero in telecom, LRIC is more representative of the shifts in costs that would be expected over the range of network scales I consider.

51 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.

52 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
[Color figure can be viewed at wileyonlinelibrary.com]



Note: 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.[53] 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.

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[53] See Online Appendix S7.

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Supporting information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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