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

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This paper develops a method to analyze the effects of competition policy in a network industry. Competition has mixed effects on incentives to invest: when a network is split between competitors, each captures only a fraction of potential network effects. However, a firm may invest in components that are not shared, to attract customers to its network. I structurally estimate the utility of adopting a mobile phone from its subsequent usage, using transaction data from nearly the entire Rwandan network over 4.5 years. I simulate the equilibrium choices of consumers and network operators, and consider Rwanda's decision to delay the introduction of competition. I show that there is a policy under which adding a competitor earlier would have reduced prices and *increased* incentives to invest in rural towers, increasing welfare by the equivalent of 1% of GDP. I analyze the effects of setting different interconnection rates, and reducing switching costs through number portability.

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1. Introduction

Many modern technologies have network effects, and as a result lead to industries with natural monopolies (consider Facebook and Google; or in earlier eras, AT&T and Microsoft). How should societies manage these industries?

Governments commonly intervene to spur competition, in the hope that consumer choice will discipline these industries. Governments can tilt the playing field by making it easier to switch, or by forcing an incumbent to connect its network to entrants (as in telecom, where regulations typically guarantee that consumers can call subscribers of competing networks). Or, governments can split up a dominant firm. However, competition splits consumers across networks, so that potential network effects are foregone. The loss of these network effects may lower incentives to invest, a concern commonly voiced by incumbent networks.[1]

This paper evaluates the effects of competition on investment and welfare in the context of mobile phone networks in sub-Saharan Africa. 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' (World Bank, 2004), and regulators have little guidance on when to tilt favor, allow consolidation (Moody's, 2015), or split firms (Reuters, 2017).

There is little empirical work to guide policy in any industry with classical network effects, where each node's adoption directly affects the adoption decisions of other nodes.[3] While there is substantial theory on classical network goods, conclusions

[1]For example, responding to a call that Facebook be split up, CEO Mark Zuckerberg said, "If what you care about is democracy and elections, then you want a company like us to invest billions of dollars a year, like we are, in building up really advanced tools to fight election interference... A lot of that is because we've been able to build a successful business that can now support that." (Kimball, 2019)

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

[3]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). There is more work on markets with indirect network effects which tend to be more tractable, including platforms and video formats (Ohashi 2003; Gowrisankaran et al. 2010; relatedly, Lee 2013). In those

depend on empirical parameters.[4] Also, 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 mostly omits factors important for growing networks such as investment and network effects in adoption.[5]

A straightforward reduced form approach would compare isolated networks in jurisdictions that set different policies. For example, Faccio and Zingales (2017) and Genakos et al. (2018) find that increases in telecom competition are associated with price reductions. However, firms choose prices and investments in anticipation of future policy. Depending on these expectations, a reduced form approach could suggest wildly different impacts of the same policy: a policy that lowers investment could appear to increase it, if firms anticipated that a more dramatic policy would be implemented. These firm expectations are typically unobservable. Even if this issue were overcome, there is too little policy variation across too few isolated networks to assess the bewildering array of policy options.[6]

If one had structural models of consumer and firm objective functions, one could evaluate an entire spectrum of policy options, under specified expectations. However, estimating a structural model of a network industry is challenging for three reasons. First, in order to capture network effects, one must estimate the demand of each individual node in the entire network. As a result, it is typically not possible to study competitive markets directly: rich network data would need to be linked between all competitors.[7] Second, it is difficult to identify network effects, because each individual's demand is a function of the demand of others in the network. One individual may adopt after a contact adopts because the contact provides network benefits, or

markets, popular platforms tend to be better served by sellers, so adopters benefit indirectly from additional users.

[4]See Katz and Shapiro (1994) and Farrell and Klemperer (2007) for review articles.

[5]With some exceptions (Valletti and Cambini, 2005).

[6]For example, even when Faccio and Zingales (2017) collapses telecom competition policy into a one dimensional index, it finds statistically insignificant quality differences between countries with different levels of concentration.

[7]I am not aware of any studies that have linked network usage data from multiple competing networks.

because connected individuals share similar traits or are exposed to similar environments. Finally, it is difficult to compute equilibria: firms' actions induce ripple effects through the entire network of demand.

This paper overcomes these challenges in the context of Rwanda's mobile phone network. I evaluate the effects of introducing competition earlier in a network industry, using 5.3 billion transaction records from the incumbent mobile phone operator, which held over 88% of the market. I find that competition would have greatly improved welfare, and there is a policy under which it would have *increased* incentives to invest in rural towers (in this case, business stealing effects dominate foregone network effects). Since my approach requires only data from an incumbent and assumptions about how a competitor would behave, it can be used by a regulator evaluating policy scenarios for an incumbent monopoly.

The Rwandan government initially limited competition in mobile telecommunications to encourage investment. When Rwanda first allowed competition, it followed common practice: each firm offered its own coverage, but firms were forced to interconnect so consumers could call customers of other networks. I study a period during which the regulator allowed entry of a second firm to compete with the incumbent in providing service. This period has two useful features. First, during this period the incumbent lowered real calling prices by 76% and nearly quadrupled the number of towers, increasing coverage from 60% to 95% of land area. Second, the competitor who did enter ended up being mismanaged in a 'quixotic' fashion (WSJ, 2006), and as a result never obtained significant market share. Because of these two features, the incumbent's data cover nearly the entire network of phones at the time, under substantial variation in price and coverage, culminating in nearly complete coverage countrywide. 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. What would have happened if this additional competitor had been granted a license earlier? Would the incumbent still have built coverage in rural areas?

I answer these questions using an empirical approach that has four parts:

First, acknowledging that the utility of owning a mobile phone is derived from its usage, I model the utility of using a phone, using the method and estimates of Björkegren (2019). Almost all phones in Rwanda are basic, prepaid mobile phones, and in the period I study mobile money did not exist.[8] I infer the value of each voice connection from subsequent interaction across that connection. This approach bypasses most of the simultaneity issues that result from inferring the value of links from correlations in adoption. Calls are billed on the margin, by the second, so a subscriber must value a connection at least as much as the cost of calls placed across it.[9] Variation in calling prices and the quality of coverage identify the underlying demand curve for communication across each link.

Second, I model the decision to adopt a mobile phone and operator. A phone provides utility by allowing communication with contacts that have phones. Consumers choose when to adopt by weighing the increasing stream of utility from communicating with the network against the declining cost of purchasing a handset.[10] I extend Björkegren (2019) to allow consumers to select and switch between operators, which may offer different price and coverage paths. I pose hypothetical questions to Rwandan consumers to estimate switching costs and idiosyncratic preferences for the entrant.

Third, I model firm decisions. As a condition for receiving a license, the Rwandan regulator required firms to submit 5 year tower rollout plans. I require firms to commit to a rollout plan as well as a path of calling prices. I assume the entrant builds towers in cities, which tend to be more lucrative, following the global strategy articulated by its parent that it later employed in Rwanda. I allow the incumbent to alter its rollout plan in response by selecting whether to increase the population threshold below which it does not build towers. I allow both firms to select a path

[8]Even as of this writing, only 9% of mobile phones in Rwanda are smartphones (ResearchICTAfrica, 2017).

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

[10]This approach has parallels with Ryan and Tucker (2012), which analyzes adoption of a videoconferencing system from its use. But in that context, individuals face no cost of use or adoption.

of prices proportional to the observed monopoly price path. To limit the multiplicity of equilibria, I require that firms charge the same rate for on- and off-network calls. These represent terms of competition that could be implemented; since the regulator may be able to do better under different terms, my results represent a lower bound of the potential welfare benefits of competition. To evaluate the cost of expanding or shrinking networks, I use engineering cost data collected under mandate by the regulator.

Fourth, to evaluate the impact of policies, I use an iterated best response algorithm to compute equilibria in a two stage game, where firms select price and rollout plans, and then consumers publicly announce adoption dates (the latter builds on Björkegren (2019)). I bound the full set of equilibria by exploiting supermodularity in both adoption and operator choices, in a manner similar to Jia (2008).

The resulting method can be used to evaluate the effect of a wide class of policies, including adding an entrant or breaking up the incumbent; changing the cost of switching operators; requiring networks to interconnect under different rates; directly regulating coverage or the price of calls; and changing taxes on handsets and airtime.

I allow an operator possessing the same parameters as the eventual entrant to enter in January 2005, and simulate the resulting firm and consumer adoption equilibria over the horizon through December 2008. I hold fixed the network and behavior of the poorly performing entrant.

I find the following:

At baseline the incumbent's mobile phone system provided net social welfare of \$334-386m, an amount equivalent to 2-3% of Rwanda's GDP over the same period.

I assess the introduction of competition under different policies, focusing on the decision to build the half of rural towers covering the lowest population. Under all interconnection policies I assess, the incumbent would find it profitable to build the selected rural towers, but the return on investment (ROI) declines as the networks are made more compatible. However, I show that there is a focal interconnection policy where competition would lower prices and *increase* incentives to investment in rural towers (allowing networks to charge each other \$0.11/minute for calls terminated across networks).[11] Under this policy, the entrant would have charged 50-60% of the monopoly rate, and the incumbent 60-70%, earning a premium for its better coverage.

I quantify three forces of competition. First, lowered prices reduce the total revenue generated by 39-41%. Second, when the network is split, network effects are foregone: 7-12% of the revenue from the incumbent's investment accrues to the entrant, holding fixed operator choices. In isolation, these two forces would make it less profitable to build these rural towers. However, there is a third force: building out rural coverage attracts marginal consumers from the other operator. Because there are many urban consumers who trade off prices and rural coverage, this business stealing effect dominates: it accounts for 64-70% of the revenue the incumbent earns from building the rural network. The balance of these forces depends on the interconnection rate; under this rate, adding a competitor would increase incentives to build rural towers; under lower rates, it would reduce incentives to invest.[12]

On net, adding a competitor under the government's suggested interconnection rates 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 official development aid over this time period. This suggests that the industrial organization of emerging networks can have profound welfare implications for the world's poorest economies.

Competition would have been unlikely to develop in absence of compatibility regulation, under these terms of competition. If the incumbent chose the terms of interconnection (and the regulator required operators to charge the same price for on- and off-net calls), the incumbent would have effectively blocked access to its network. This outcome is similar to that in Somalia, where during an unregulated period it was not possible to call from one mobile phone network to a competing one, and is reminiscent of many network industries that do not endogenously develop compatibility (Katz and Shapiro, 1985).

[11] This rate is 25% higher than the rate the government had set at the time.

[12] These results are similar in flavor to Goettler and Gordon (2011), which finds that the effect of competition on investments in innovation can vary based on industry primitives.

I also assess the effects of changing switching costs, different interconnection rules, and different entry dates.

To my knowledge, this represents the first empirical analysis of competing classical network goods using micro data. It builds on the network demand system developed in Björkegren (2019), which in that paper is used to assess the impact of taxes and a coverage requirement on a monopoly network. It is related to Ryan and Tucker (2012), which analyzes how encouraging individuals to adopt a corporate videoconferencing system affects the adoption of other nodes.

My modeling choices differ from those commonly made for nonnetwork industries. In nonnetwork models it is common to treat individual consumer decisions as independent, or to aggregate demand. Neither of these approaches account for foregone network effects, because they rule out ripple effects (which in the same setting account for 61% of the effect of handset taxes on telecom revenues per Björkegren (2019)).[13] Because the shape of network effects depends crucially on the network structure of demand, the focus of this paper is developing a tractable industry model that correctly accounts for network effects, with a supply side that captures the essential features of competition in a feasible policy environment. Because I model the full structure of the network, my results factor in the position of each node in the network: an isolated node will tend to have less spillover effects than a central node, independent of the intensity of its links. I focus on how investment is affected by splitting a network, not intertemporal tradeoffs in investment; I do not find that results are sensitive to firms' time horizons. Because the incumbent already expected a firm to enter in 2005 and did not know its type, one would expect any predation to be built in to starting conditions. Developing further richness on the supply side is left to future work (at which point I am optimistic that computational constraints may be eased).

My approach has two limitations. First, like a regulator in the position of deciding to handle a monopoly network, I do not observe network usage data from a period of

[13] A simple aggregation of demand by location would also fail to capture the force which I find ends up being most important for effect of competition on investment: investment in coverage induces large business stealing effects, from people who live in urban areas but sometimes travel to rural areas.

effective competition. However, I am able discipline my models of firm and consumer behavior using other sources of data from other markets that were competitive at the time, and from Rwanda after the market became competitive. Second, 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.

2. Conceptual Framework

Consider a network of potential consumers $\mathbf{G}$, each deciding about using a network good offered by firms $a \in A$. Each consumer $i \in \mathbf{G}$ takes an action $x_i^a(\mathbf{x}_{-i}, p, \phi_i^a)$, which depends on the actions of others in the network, $\mathbf{x}_{-i}$ and the price p. ϕ_i^a is a nonnetwork dimension of quality which may be differentially useful to different individuals (for example, cellular coverage or a particular feature).

Consider incentives to invest in quality under different market structures:

Monopoly. The firm's profits depends on consumers' actions:

$$\pi^{monopoly}(p, \boldsymbol{\phi}) = \sum_{i \in \mathbf{G}} p \cdot Q_i(\mathbf{x}(p, \boldsymbol{\phi})) - c(\boldsymbol{\phi})$$

where $\mathbf{x}(\cdot)$ represents an equilibrium in actions, $p \cdot Q_i(\cdot)$ is the associated revenue, and and $c(\boldsymbol{\phi})$ is the cost of investment.

Consider the impact of increasing the quality available to i: increasing ϕ_i has two effects on profit:

$$\frac{d\pi^{monopoly}}{d\phi_i} = p \cdot \frac{\partial x_i}{\partial \phi_i} \cdot \left[\underbrace{\frac{\partial Q_i}{\partial x_i} \cdot}_{\text{Proximal effect}} + \underbrace{\sum_{k \in \mathbf{G}} \left[\sum_{\text{all paths } i \to k \in \mathbf{G}} \frac{\partial x_{j_1}}{\partial x_i} \cdots \frac{\partial x_k}{\partial x_{j_N}} \right] \frac{\partial Q_k}{\partial x_k}}_{\text{Ripple effects}} \right] - \frac{\partial c}{\partial \phi_i}$$

As in standard goods, ϕ_i directly influences i's action (a proximal effect). But when demand is networked, changing i's action also induces ripple effects, through all paths in the network, until $\mathbf{x}$ reaches an equilibrium. In the same setting as this paper, Björkegren (2019) finds that ripple effects account for 61% of the effect of handset taxes on telecom revenues in a growing network. Standard demand models neglect ripple effects, and can mischaracterize outcomes in network industries.

Competition. Potential entrants face two barriers. First, consumers may directly prefer to use a network that has more users. But also, larger networks also have larger incentives to invest in nonnetwork dimensions of quality, because they internalize more ripple effects. Thus, when demand is networked, quality differentials tend to reinforce the dominance of large networks, even in absence of scale economies in cost.

If a network industry were able to sustain competition, competition would have three effects on incentives to invest. First, firms may lower prices, lowering overall revenues. Second, because competition splits the network, some network ripple effects are foregone.[14] Third, firms may invest to induce marginal consumers to switch networks (a business stealing effect).[15]

Competition may reduce or increase the returns to investing in a network, depending on whether the business stealing effect is larger than the foregone network effects and lower overall revenues. This balance depends on how responsive each node is to quality ϕ_i, and the structure of the network.

This paper develops a method to empirically assess these equilibrium tradeoffs in an important real world network with 1.5 million nodes and 415 million links: the Rwandan mobile phone network. I focus on the main investment during this period, coverage (ϕ_i).

3. Context

Developing country phone systems. Between 2000 and 2011, the number of mobile phone subscriptions in developing economies increased from 250 million to 4.5 billion (ITU, 2011). As component costs decreased, handsets became accessible even

[14]If the networks are incompatible, the network effects will ripple only within a firms' own network; other potential spillovers are foregone. If the networks are compatible, network effects may instead spill over into competing networks.

[15]This business stealing effect may also ripple through the network.

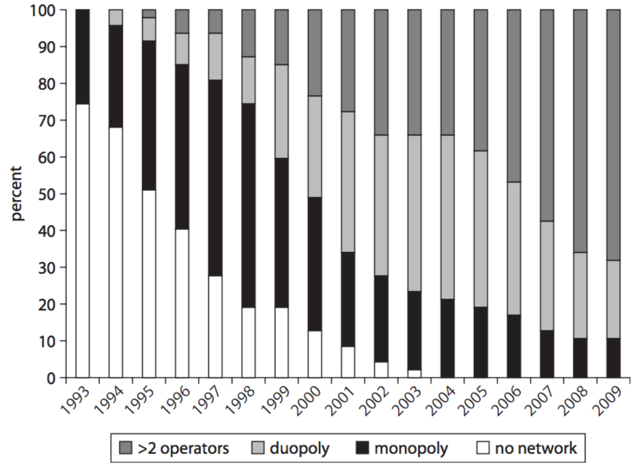
to the poor, and operators expanded coverage to increasingly remote regions. (In 2005, the cheapest mainstream handset in Rwanda cost roughly $70, or 3.5 months of the mean person's consumption; by 2009 handsets were available for $13.)

As these networks grew, regulators licensed multiple operators to compete in providing service (see Figure 1), recognizing that monopoly networks may underserve the market when price discrimination is imperfect. However, it is difficult for entrant networks to compete unless they can connect to incumbent networks. Left to the market, incumbents typically demand prohibitively high fees for interconnection, preventing competition (the 'one way' access problem). Even when network sizes are balanced, firms can use interconnection rates as an instrument of collusion (the 'two way' access problem: Armstrong, 1998; Laffont et al., 1998). Thus, most regulators intervene to set the terms of interconnection, commonly to a function of costs (the World Bank (2004) model represents a benchmark).

But there is little consensus on the optimal ground rules for competition. Table 1 summarizes the diversity of current industry statistics and regulations in sub-Saharan Africa. Increases in competition have been followed by calls for consolidation; and in East Africa between 2010 and 2015, only one country saw net entry of a telecom operator while three countries had net exit. While most countries regulate interconnection prices, they consider different information to determine levels, and allow different amounts of complexity. Different theoretical models suggest different optimal interconnection rates, and most telecom theory is designed for mature developed country networks, and does not consider how policies affect network growth.

Rwanda. In the aftermath of the genocide and civil war, the Rwandan government in 1998 granted a license to a multinational operator to develop and run a mobile phone system (Operator A); it was understood that this license would be exclusive for a limited period. Rwanda allowed the operator to set consumer prices at its discretion. Most of the coverage investments were driven by market incentives (Björkegren,

Figure 1. Mobile Telecom Competition in sub-Saharan Africa



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

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%	
...asymmetrically between operators	31%	

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.

2019), but attached to the license was a requirement that the operator build out rural coverage in a small number of priority areas.[16]

In 2003, the government announced it would provide a license to a second mobile operator, which entered the market in 2006 (Operator B). This second operator turned out to be troubled and unsuccessful. It was a subproject of the former state landline company, but was initially purchased by an American satellite entrepreneur described

[16]These included border crossings, major roads, and district centers.

as 'quixotic' (WSJ, 2006).[17] After several changes in ownership (including by part of the Libyan government), 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.[18]

In an effort to push competition, the Rwandan regulator granted a license to a third multinational operator (Operator C), which entered the market at the end of 2009 with aggressive prices. The multinational articulated a strategy to cover urban areas in its African markets, which is the strategy it followed when it entered Rwanda.[19] Its entry spurred an interconnection dispute: the regulator hired a consultant, who used detailed cost data from operators to recommend lowering interconnection rates along a glide path (see Argent and Pogorelsky, 2011; PwC, 2011; RURA, 2009).

In 2011 a new operator, Operator D, absorbed the assets and license of Operator B. 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. The coverage plot shows that despite being able to build on the incumbent's towers, entrants' networks offer less complete coverage.

This paper uses data from the period 2005-2009. The calling price plot shows the baseline calling price, and foreshadows the result of a focal counterfactual where Operator C is granted a license in 2005 at an interconnection rate of $0.11 per minute.

Consumer choice. The ability of competition to discipline firms depends on how consumers choose between them. Table 2 shows the results of a Research ICT Africa survey of phone owners in several sub-Saharan African countries.

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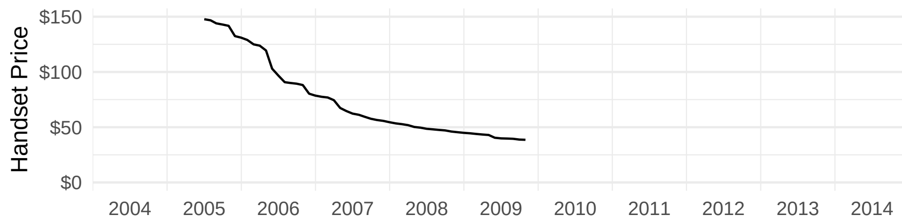
[17]That article reports that the operator 'had no customer-service department and 12 employees whose sole job was to play on the company soccer team.'

[18]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."

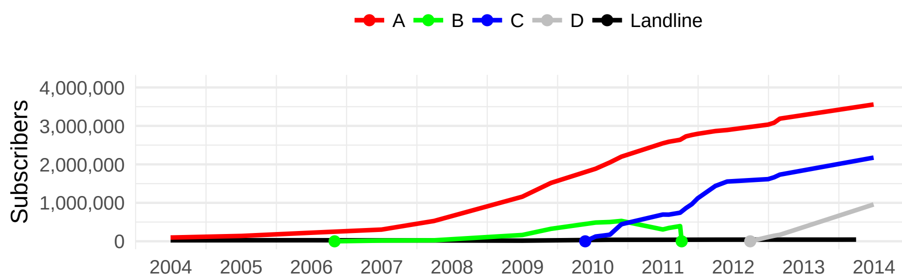
[19]Operator C's global Annual Report in 2010 said: 'There is scope for further coverage growth in our African markets, but urban centers currently represent the significant majority of the addressable population and we believe that the right approach to reaching more rural areas is increasingly to share network infrastructure with other operators.' Tower sharing in Rwanda was limited until it was mandated by the regulator in 2011.

FIGURE 2. Development of Telecommunications in Rwanda

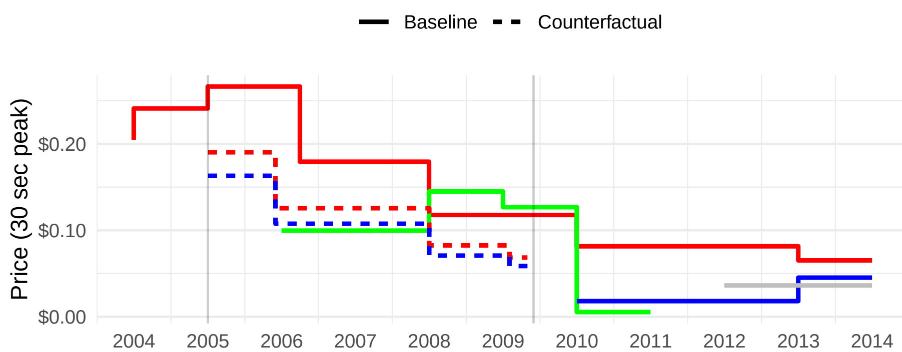
(a) Handset Price (real, quality adjusted index)



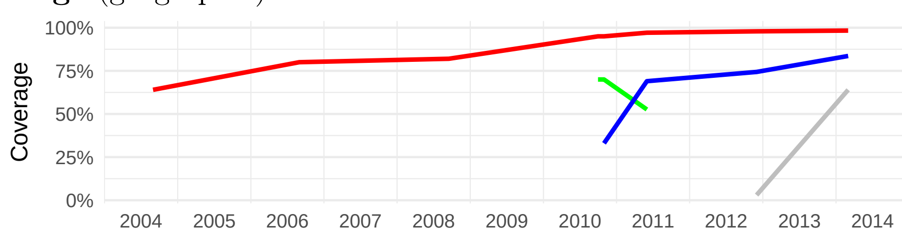
(b) Accounts



(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 focal counterfactual where Operator C enters in 2005 with an interconnection rate of $0.07 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.

In Rwanda, almost all phone plans are prepaid, with no monthly fee but a marginal charge by second of talk time.[20] Handsets are standard, imported models, with prices that track global trends. Most are purchased from independent sellers.[21] I consider the handset market as perfectly competitive, with availability and prices unaffected by the market for cellular service.

During this period, phones were used primarily for voice calls. Mobile money did not exist in Rwanda. I do not explicitly model utility from SMS, missed calls, international calls, and calls from payphones.[22] Any value these omissions provide will be captured in a residual when I estimate the adoption decision.

I develop a model to capture the key differentiators (coverage and pricing).

[20]See Supplemental Appendix: Operator Differentiators for more details.

[21]Operator handset sales records account for only 10% of total handsets activated during the period of my data.

[22]From the data it is not possible to match the sender and receiver of a given SMS. Though important in other contexts, in Rwanda text messaging or SMS was high priced ($0.10 per message) and represented less than 13% of revenue and 16% of transactions. Only calls that are answered incur a charge; so subscribers may communicate simple information with missed calls (Donner, 2007). But it is difficult to distinguish between missed calls that provide utility (communicating information) and those that provide disutility (due to network problems or inability to connect).

4. Data

This project uses several data sources:[23]

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 anonymous call records from the dominant Rwandan operator, which held above 88% of the market during this period. This data includes nearly every call, SMS, and top up made over 4.5 years 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 the competing operator. For each transaction, the data reports: 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.[24] I aggregate durations to the monthly level.

Operator costs: Following common practice, the Rwandan regulator regularly 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 study conducted for Rwanda by international consultants (PwC, 2011), which was crosschecked against regional and international benchmarks.

Coverage: A rollout plan, $\mathbf{z} = \{(t_z, x_z, y_z)\}_z$, is defined by tower build dates and geographical coordinates. I consider the baseline rollout, $\mathbf{z}_{(100\%)}$, as well as counterfactual rollouts that trim rural towers. 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: Because handsets are mobile, an individual may make calls from several locations, such as a village and the capital. I infer the

[23]For more information see Supplemental Appendix.

[24]Some months of data are missing; from the call records: May 2005, February 2009, and part of March 2009. The locations of 12% of tower identifiers are missing from this data; I infer their location based on call handoffs with known towers using a procedure I have developed (Bjorkegren, 2014).

geographical coordinates of each subscriber i's set of most used locations, $\{(x_{il}, y_{il})\}_l$, based on their eventual calls, using an algorithm analogous to triangulation (a version of Isaacman et al. (2011) that I have modified to improve performance in rural areas). Because individuals may use the phone in the area surrounding each location, I compute a smoothed coverage map, where $\phi_t(x, y; \mathbf{z})$ represents an average of the coverage available near (x, y) under rollout plan $\mathbf{z}$, weighted by a two-dimensional Gaussian kernel with radius 2.25km. I compute an individual specific coverage sequence by taking the average of the coverage at each individual's important locations weighted by the days spent at each location, d_{il}: $\phi_{it}(\mathbf{z}) = \frac{\sum_l \phi_t(x_{il}, y_{il}; \mathbf{z}) \cdot d_{il}}{\sum_l d_{il}}$.

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: I fielded a small consumer survey in Rwanda in the summer of 2017, to determine how consumers select between mobile phone operators in a competitive market.

5. Model

The incumbent $t = 0$ with an initial set of subscribers and towers, based on its historical choices. The government announces a policy environment (competitor entry date, and interconnection terms $\boldsymbol{f}$), and the game proceeds in three steps. First, the entrant selects a path of prices $\mathbf{p}^1$, and commits to build towers in urban areas. Second, the incumbent selects a path of prices $\mathbf{p}^0$ and a tower rollout plan $\mathbf{z}^0$. Third, each consumer decides when to adopt a phone (x_i), and each period decides which operator to use ($a_{it} \in \{0, 1\}$, either the incumbent or entrant), and how many seconds to call each contact ($d_{ijt} \geq 0$). This model of phone usage is extended from Björkegren (2019) to allow for competition. I describe the model in reverse.

5.1. **Consumers.**

The primary unit of observation is an account, which corresponds to a phone number. I assume that each account is associated with a unitary entity such as an individual, firm, or household.[25] For ease of exposition I refer to accounts as individuals or nodes.

Let $\bar{G}$ be the 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 $S_T^0 \subseteq N$. Because I only observe a link if a call was placed, I observe the subgraph, $G_T^0 \subseteq \bar{G}$, where $ij \in G_T^0$ if i has called j by period T while both subscribed to the incumbent.[26] As shorthand, define $G_i = \{j \,|ij \in G_T^0\}$ as i's set of contacts. The graph I observe omits any 'dark' nodes $i \in N \backslash S_T$ who may have adopted if conditions were more favorable; I report results only up to a horizon $\tilde{T} \leq T$ prior to which these nodes would affect results.[27]

In estimation and baseline simulations, each individual $i \in S_T$ may select only the incumbent operator ($a_{it} = 0$); I refer to this baseline market structure as monopoly. In counterfactuals, each individual $i \in S_T$ may select either the incumbent or the new entrant ($a_{it} \in \{0, 1\}$).

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

[25] If the composition of people using a handset changed over time (say, if a couple initially shares a phone but later obtains separate phones and splits its communication), then the communication graph I estimate will be similar to a weighted average of the underlying networks. See Supplemental Appendix S1 for more discussion.

[26] This will miss any links between subscribers where there is a latent desire to communicate but no call has been placed by T ($G_T^0 \subseteq \bar{G}_T^0$). See Supplemental Appendix.

[27] The network I observe omits the small number of individuals who subscribed to the incumbent's first competitor, less than 12% of the market; I assume that these individuals' usage remains the same in any counterfactual.

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

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

I model the benefit of making calls as:

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

for $\epsilon > 0$, where the first term represents 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.[28]

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

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

where $p_t^{a_{it} a_{jt}}$ is the per-second calling price for a call from firm a_{it} to a_{jt} (including any tax). I will impose the regulatory restriction that firms charge the same price for on- and off-net calls ($p_t^{a_{it} a_{jt}} = p_t^{a_{it}}$). Each firm offers its own coverage; if i subscribes to firm a in month, he will receive coverage $\phi_{it}^a \in [0, 1]$, derived from the fraction of the area surrounding his most used locations within line of sight of the firm's towers. $\beta_{coverage} \phi_{it}^{a_{it}} \phi_{jt}^{a_{jt}}$ 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:

$$(2) \qquad d(\epsilon, \mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) = \left[\epsilon \left(1 - \beta_{cost} (p_t^{a_{it} a_{jt}} - \beta_{coverage} \phi_{it}^{a_{it}} \phi_{jt}^{a_{jt}}) \right) - \alpha \right]^{\frac{1}{\gamma - 1}}$$

[28]This functional form was chosen to satisfy 8 reasonable properties for the utility from telephone calls; see Björkegren (2019).

which increases with the desire to communicate (ϵ) and decreases with cost. $\mathbf{p}_t$ represents the vector of prices by firm, $\boldsymbol{\phi}_t$ represents the vector of coverage by individual and firm, and $\mathbf{a}$ represents firm choices for each individual. If the desire to communicate is not strong enough, i does not call: $d_{ijt} = 0$ when $\epsilon_{ijt} \leq \underline{\epsilon}_{ijt} := \frac{\alpha}{1-\beta_{cost}\left(p_t^{a_{it}a_{jt}} - \beta_{coverage}\phi_{it}^{a_{it}}\phi_{jt}^{a_{jt}}\right)}$.

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

$$Ed_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) = \int_{\underline{\epsilon}_{ijt}}^{\infty} d(\epsilon, \mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) \cdot dF_{ij}(\epsilon) \tag{3}$$

and provide expected utility:

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

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

$$Eu_{it}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}, \boldsymbol{x}_{G_i}) = \sum_{j \in G_i \text{ and } x_j \leq t} Eu_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) - s \cdot 1_{\{a_{it} \neq a_{it-1}\}} \tag{4}$$

where x_j represents j's adoption time and s represents the cost of switching operators.[29]

However, at the point of adoption, i anticipates that having a phone in month t will provide utility:

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

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 to make simulation tractable I do require that each individual's type is constant over time and across counterfactuals. Each month that i does not have a phone he receives utility zero.

[29] This would include the cost of changing accounts (swapping SIM cards and adjusting any settings), and notifying contacts about the change in phone number. Björkegren (2019) also considers the possibility that consumers receive value from incoming calls, but finds that this double counts the utility from calls.

Adoption decision. Conditional on the decisions of others, an individual's adoption decision is an optimal stopping problem. That decision proceeds in two steps:

First, consumer i decides when to purchase a handset, with beliefs about which operators his contacts use. At period t, i knows the current price of a handset, $p_t^{handset}$ (inclusive of any tax), and knows that his contacts will adopt at times $\boldsymbol{x}_{G_i}$. He has deterministic beliefs over two objects, described fully in the Equilibrium section. He believes that in period $x > t$, the handset price will be $E_t p_x^{handset}$, and that contact j will use the operator $\hat{\mathbf{a}}_j(\mathbf{p}, \boldsymbol{\phi}_j, \boldsymbol{\phi}_{median})$ that is optimal for calls to the median individual, given prices and coverage in j's location. He thus expects the utility of adopting at time x with operator sequence $\mathbf{a}_i$ to be:

$$E_t U_i^{\mathbf{a}_i,x}(\mathbf{p}, \boldsymbol{\phi}, \boldsymbol{x}_{G_i}, \hat{\mathbf{a}}_{G_i}) = \delta^x \left[\sum_{s \geq x}^{\infty} \delta^{s-x} E\hat{u}_{is}(\mathbf{p}_s, \boldsymbol{\phi}_s, \left[\mathbf{a}_i, \hat{\mathbf{a}}_{G_i}\right], \boldsymbol{x}_{G_i}) - E_t p_x^{handset} \right] \tag{5}$$

i adopts in the first month x_i where he expects adopting immediately to be more attractive than waiting, given his beliefs about contacts' adoptions:

$$\min\ x_i\ s.t. \left[\max_{\mathbf{a}_i} E_{x_i} U_i^{\mathbf{a}_i,x_i}(\mathbf{p}, \boldsymbol{\phi}, \boldsymbol{x}_{G_i}, \hat{\mathbf{a}}_{G_i}) \geq \max_{s > x_i, \tilde{\mathbf{a}}_i} E_{x_i} U_i^{\tilde{\mathbf{a}}_i,s}(\mathbf{p}, \boldsymbol{\phi}, \boldsymbol{x}_{G_i}, \hat{\mathbf{a}}_{G_i}) \right] \tag{6}$$

Second, upon purchasing a handset, consumer i learns his contacts' operator choices, and selects operator sequence $\mathbf{a}_i$ to maximize utility (under updated beliefs $\hat{\mathbf{a}}_j = \mathbf{a}_j$).

In counterfactuals, I allow consumers to delay adoption beyond the end point of the data $\bar{T} > T$, but report outcomes only up to the dark network horizon $\tilde{T} \leq T$.

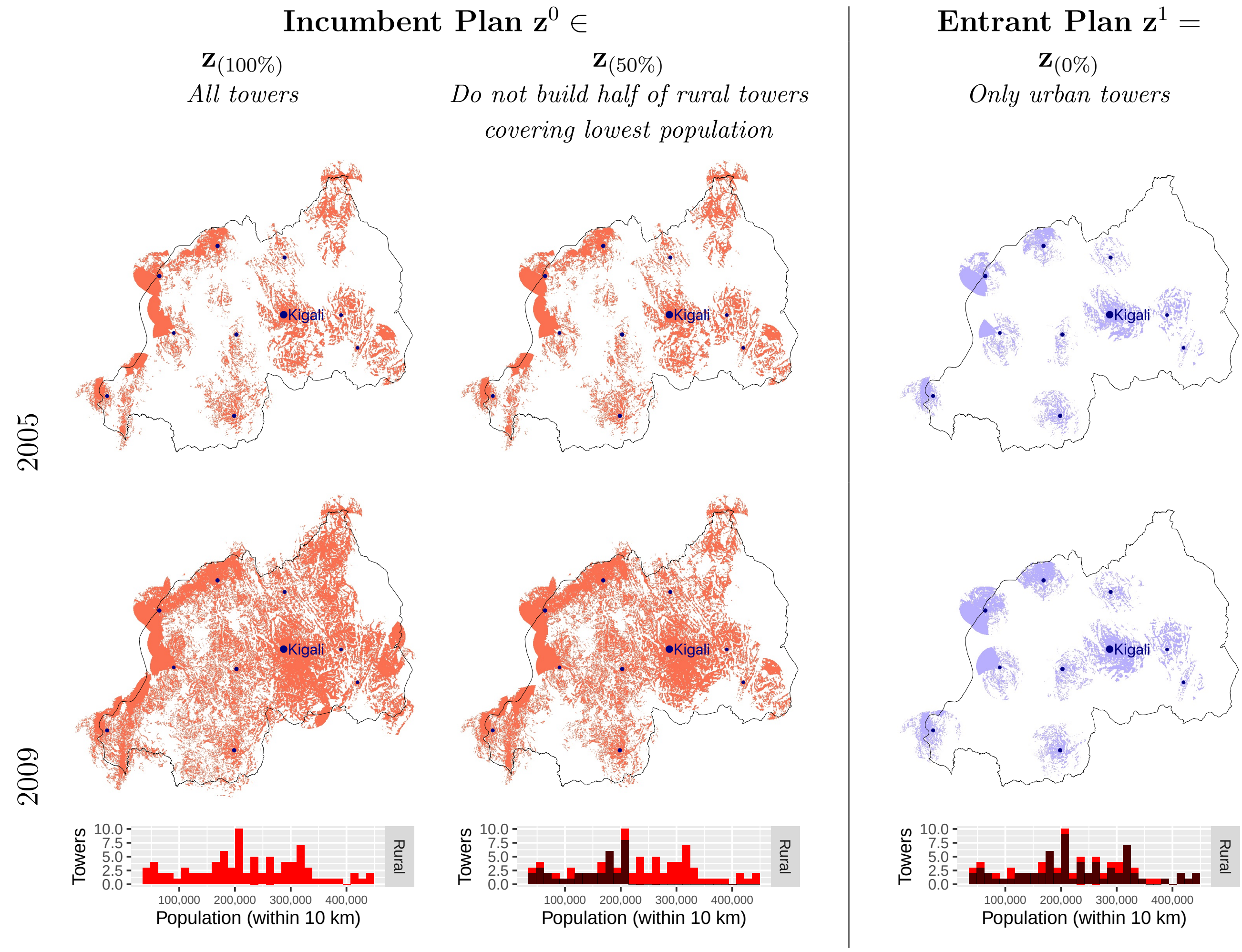
Consumer surplus. The expected net present value of consumer surplus through $\tilde{T}$ is given by:

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

which is net of calling, handset, and hassle costs. I assume handsets are provided by a competitive market at marginal cost, and are sold back at the end of the horizon at the prevailing price.

5.2. **Firms.** As a condition for receiving or renewing a license, regulators commonly require mobile telecoms to submit tower rollout plans; in Rwanda, these specify towers

Figure 3. **Rollout Plans**



Coverage shaded; points denote cities. Under the observed incumbent rollout, the regions without coverage in the northeast and southwest are national parks.

to be constructed over a horizon of 5 years.[30] In my model, each firm F commits to a path of calling prices and a tower building plan $\mathbf{z}^F$ through horizon $\tilde{T}$ to maximize profits:

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

Firms may select calling prices from a multiple of the monopolist price path: $\mathbf{p}^F \in \psi \cdot \mathbf{p}^{monopoly}$, given grid $\psi \in \{0.1 \cdot n | n \in 1...10\}$.

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

It tends to be more lucrative to build towers in more populous areas: they cover more people and operating costs tend to be lower. I assume firms build the same urban towers as baseline. I rank rural towers by an index of desirability, the population within a 10 km radius, and allow firms to pursue a monotone cutoff strategy. I assume that the entrant follows its parent company's articulated strategy in Africa (and later entry in Rwanda) and builds only urban towers: $\mathbf{z}^1 = \mathbf{z}_{(0\%)}$. I allow the incumbent to build out nearly complete coverage, or only the 50% of rural towers covering the highest populations: $\mathbf{z}^0 \in \{\mathbf{z}_{(100\%)}, \mathbf{z}_{(50\%)}\}$ (see Figure 3).

Firm F earns revenue from the calls of their own subscribers and from interconnection fees charged to the competitor's subscribers who call in to the network:

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

where $\boldsymbol{\phi}_t(\mathbf{z})$ is the coverage provided at time t under the rollout plans $\mathbf{z} = \{\mathbf{z}^0, \mathbf{z}^1\}$, τ_{it}^{usage} represents the airtime tax rate, and f_{ij} is the interconnection rate.

Firm F incurs costs:

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

K_{rural} represents the annualized cost of owning and operating a rural tower.[31] Each month that its network is operational, operator F also incurs fixed cost fc^F. $ic_{L_i, onnet_{ij}}^{direction}$

[31]In Rwanda during this period, mean monthly revenue from an urban tower is nearly twice that of a rural tower. The total annualized cost of owning and operating a tower in Rwanda is $51,000 per year, plus $29,584 for towers that are far from the electric grid that must be powered by generators. I define a tower as urban if it covers Kigali or one of Rwanda's 5 largest towns; a subscriber is defined as urban if his most used tower is urban.

is the incremental cost of sending or receiving an additional second, including switching equipment, staff, central operations, and costs of capital, for $direction \in \{in, out\}$. I allow the cost to vary by whether the two parties are on the same network, and whether each subscriber is primarily urban or rural ($L_i \in \{\text{urban}, \text{rural}\}$).

Although in practice firms would make decisions anticipating the full stream of profits into the future, because my data has an end date, I assume firms maximize net present profits through horizon $\tilde{T}$.[32]

Discussion. This action space rules out the possibility that the entrant would have used a different coverage strategy had it entered the market when the network was smaller and handset prices were higher.[33]

5.3. **Government.** The government decides whether to grant a license to the entrant firm, and if so, decides how to set the interconnection policy f_{ij}. It earns revenue:

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

This includes revenue from taxes on adoption ($\tau_{it}^{handset}$) and usage (τ_{it}^{usage}), which I hold fixed.[34] I do not take a stand on whether the government maximizes welfare, revenue, or another objective.

5.4. **Equilibrium.** An equilibrium reconciles firm choices with the network of consumer choices. Formally,

[32]As a result, firms undervalue their stock of subscribers at $\tilde{T}$. In the Supplemental Appendix I find that results to not differ substantially under different choices of $\tilde{T}$, including when the final period T is repeated for three years.

[33]The Supplemental Appendix shows that 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. Although it is theoretically possible that firms would divide up the country to serve different territories, such arrangements are illegal under common antitrust laws.

[34]At the time, Rwanda taxed handsets at 48% and usage at 23%.

Given consumer types $\boldsymbol{\eta}$, interconnection terms $\boldsymbol{f}$, and horizon $\tilde{T}$,

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

1. The entrant selects price sequence $\mathbf{p}^1$, and constructs urban towers $\mathbf{z}^1 = \mathbf{z}_{(0\%)}$

2. The incumbent selects price sequence $\mathbf{p}^0$ and tower construction plan $\mathbf{z}^0$

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 $\mathbf{d}$ such that:

- Each initial adopter $i \in S_0$ selects operator sequence $\mathbf{a}_i \in \{0,1\}^{\bar{T}}$ optimally according to Equation 6, believing each contact j will adopt at time x_j using operators $\mathbf{a}_j$
- Every other observed adopter $i \in S_T \backslash S_0$ selects:
  - adoption date $x_i \in \{1, ..., \bar{T}\}$ optimally according to Equation 6, believing each contact j will adopt at time x_j using operators $\hat{\mathbf{a}}_j(\mathbf{p}, \boldsymbol{\phi}_j, \boldsymbol{\phi}_{median})$
  - operator sequence $\mathbf{a}_i \in \{0,1\}^{\bar{T}-x_i}$ optimally according to Equation 6, believing each contact j will adopt at time x_j using operators $\mathbf{a}_j$
- After adoption, $i \in S_T$ calls each contact $j \in G_i \cap S_t$ for $d_{ijt} = Ed_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a})$ seconds in month t, per Equation 3

5.5. Expectations.

Firms. Given firm actions, there are many potential adoption equilibria: consumers may coordinate on adopting early or late, or favoring the incumbent or entrant. I restrict consideration to overall equilibria where firms anticipate a degree of continuity in the subgame equilibria played by consumers. If consumers play an equilibrium of some index e in the subgame resulting from actions $(\mathbf{p}^0, \mathbf{p}^1, \mathbf{z}^0, \mathbf{z}^1)$, firms believe that in the subgame resulting from actions $(\mathbf{p}^{0'}, \mathbf{p}^{1'}, \mathbf{z}^{0'}, \mathbf{z}^{1'})$, consumers will play a related equilibrium, also of index e. Conditional on consumers adopting according to e, the overall equilibrium is unique.

I focus on families of equilibria $\underline{e}^A$ and $\bar{e}^A$, which are indexed along two dimensions along which consumer adoption equilibria form a lattice:

First, I index whether the consumer adoption is lowest ($\underline{e}$) or highest ($\bar{e}$). In the first, consumers adopt as slow as possible given prices and coverage; in the second, consumers adopt as fast as possible given prices and coverage. These are defined because adoption equilibria form a lattice: 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 $\phi_j^{a_j}$.[35]

Second, I index whether operator choices favor the incumbent ($A = 0$) or entrant ($A = 1$) (similar to Jia (2008)). Conditional on adoption dates, consumers weakly prefer to be on the same network as their contacts, because coverage choices are complementary and on-net calls are no more expensive than off-net calls.[36][37]

Consumers. Within equilibrium e, individuals correctly forecast call prices p_x, coverage $\boldsymbol{\phi}_x$, and their contacts' adoption dates $\boldsymbol{x}_{G_i}$. At the point of adoption, consumers use forecasts of handset prices $p_t^{handset}$ and contacts' operator choices $\mathbf{a}_j$.

Because a handset becomes sunk at the time of purchase, forecasts of future prices can sway the adoption decision.[38] I assume that at each period t, individuals learn the current handset price and expect the price in future periods to decline at an exponential rate consistent with the overall decline over this period:

$$E_t p_x^{handset} = \omega^{x-t} p_t^{handset}$$

for $\omega = \left(\frac{p_T^{handset}}{p_0^{handset}}\right)^{\frac{1}{T}}$.

[35] A higher type η_i^a weakly decreases i's optimal adoption date, and a decrease in i's adoption date x_i or coverage $\phi_i^{a_i}$ weakly decreases j's optimal adoption date. This follows from the lattice structure of $\boldsymbol{x}$ and because $U^{x_i}(\eta_i, \boldsymbol{x}_{-i}, \boldsymbol{\phi}_i)$ has increasing differences in x_i and x_j, or is supermodular in $\boldsymbol{x}$; see Topkis (1978) and Milgrom and Shannon (1994).

[36] Coverage choices are complementary because an individual's and his contact's coverage enter costs multiplicatively.

[37] 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 adoption equilibrium, this 'punishment' could induce firms to set a lower price than if they believed that consumers would consistently adopt according to similarly optimistic or pessimistic equilibria in each subgame. Similarly, if firms believed that when $\mathbf{p}^F \equiv \tilde{\mathbf{p}}$, the equilibrium will favor F, but for $\mathbf{p}^F \neq \tilde{\mathbf{p}}$ the equilibrium will favor $-F$.

[38] I model these forecasts in order to rationalize a small number of consumers who purchase handsets in months that precede large declines in handset prices.

Prior to purchasing a handset, consumers have deterministic beliefs about which operators their contacts have selected. i believes that each contact j will use the operator that is optimal given prices and coverage at j's location, for calls to the median individual at month T.[39] This avoids nonmonotonicities in adoption equilibria. Once i has purchased a handset, he selects an operator anticipating contacts' actual operator choices ($\hat{\mathbf{a}}_j = \mathbf{a}_j$).[40]

Together, this notion corresponds to an equilibrium of a game where each individual adopts at the first sufficiently attractive date, based on actual contact adoptions, and expected path of handset prices and contact operators. It 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.[41] 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.

If at the point of adoption, an individual forecasts differently than specified here, the error will be captured in his type (η_i^0, η_i^1), as long as the error is fixed across time and counterfactuals. In the Supplemental Appendix, I also consider a model where consumers correctly anticipate their contacts' actual operator choices, but equilibria are only approximate; I find that results are similar.[42]

This notion allows for rich behavior: a perturbation of utility that causes one individual to change their adoption date can shift the equilibrium, inducing ripple effects through potentially the entire network. Firms internalize revenue from network effects

[39] That is, $\hat{\mathbf{a}}_j(\mathbf{p}, \boldsymbol{\phi}) = \arg\min_a \left[p_T^{aa_m} + \beta_{coverage}\phi_{jT}^a \phi_{mT}^{a_m}\right]$, for median individual m, who selects his operator analogously: $a_m = \hat{\mathbf{a}}_m(\mathbf{p}, \phi_m)$.

[40] In the Supplemental Appendix, I find that if instead consumers correctly anticipate their contacts operators at the point of adopting a handset, adoptions do not always converge to an equilibria, but are very close to the results with this belief structure.

[41] This results in an open loop equilibrium; see for example Fudenberg and Levine (1988).

[42] To assess the importance of forward looking behavior, Björkegren (2019) also estimates and simulates results under a myopic model where individuals do not consider the future in their adoption decision, for the monopoly case. Results are similar in character.

in their own networks, but not from network effects that spill over into competing networks, except that partially recovered through interconnection fees.

6. Estimation

I combine estimates from a monopoly setting with supply side costs and additional parameters characterizing choice under competition.

Consumer decisions when there is a single operator. Individuals choose when to adopt a mobile phone and, if they adopt, how to use the phone. The decision to use a phone directly reveals the value of each connection, overcoming traditional issues with identifying the value of network goods solely from the decision to adopt. Call decisions reveal the country's latent communication graph (the call shock distributions F_{ij}), the shape of the utility function (γ and α), and how usage responds to cost (β_{cost} and $\beta_{coverage}$). The adoption decision reveals any residual factors affecting adoption of the incumbent (bounds on individual types $[\underline{\eta}_i^0, \bar{\eta}_i^0]$). I use the estimation method and estimates of Björkegren (2019), described in Appendix A.

Consumer decisions with multiple operators. To estimate the costs of switching, and idiosyncratic preferences for the entrant, I posed hypothetical incremental switching exercises to mobile phone owners in Rwanda (see Supplemental Appendix).

Switching operators entails changing phone numbers, coverage, and learning new short code commands. The mean switching cost is $s = \$36.09$, 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.[43]

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

[43]In counterfactuals in Section 9, I find that the switching cost has a small effect on counterfactual results.

preference for one operator's branding or color scheme. In counterfactual simulations, I treat these differential preferences as random parameters: for each individual I draw $e_i \overset{iid}{\sim} N\left[m(\eta_i^0 - \eta_i^1), \sigma(\eta_i^1 - \eta_i^0)\right]$, and compute his type under the entrant $[\underline{\eta}_i^1, \bar{\eta}_i^1] = [\underline{\eta}_i^0 - e_i, \bar{\eta}_i^0 - e_i]$. To reduce the computational burden, I present results from a single random draw; in a robustness test in the Supplemental Appendix, I find that the random draw has little effect on outcomes.

Validation. I validate the quality of hypothetical responses by comparing to an analogous choice. From actions in the data, I estimate that the cost of switching between plans on the same operator is much lower, \$6.83. I find that this does not differ significantly at the 1% level from an estimate from analogous hypothetical choices.[44]

The Supplemental Appendix also assesses the extent to which the model matches behavior observed under competition in Rwanda and in similar countries that were competitive at this time.

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

I infer 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 a detailed engineering breakdown of the network, using cost estimates obtained from operators, crosschecked against international benchmarks. 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.[45] 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%)

[44]For part of this time, the operator offered two plans, which billed by the minute or the second: see Björkegren (2014). For most subscribers, per second billing was a price reduction; I model its introduction in 2006 as a price decline.

[45]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.

after identifying the size of the firm in equilibrium.[46] Second, I remove the license fee paid to the regulator, which represents a pure transfer. Third, I separate out the cost of rural tower investments. In urban areas, towers tend to be capacity constrained so that the number of towers scales with call volumes; however, in rural areas, the number of towers scales instead with coverage. For subscribers who primarily use urban towers ($L_i = urban$), I include the cost of towers in incremental costs. For subscribers who primarily use rural towers ($L_i = rural$), I compute the cost of towers separately.

I infer 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.[47]

Validation. Because Rwanda's regulator does not intervene in consumer telecom prices, the monopolist's price choices allow a consistency check on these cost estimates. I find that under these cost estimates, the monopolist's chosen prices are profit maximizing (see Supplemental Appendix).

Costs appear similar to other African markets. Although the cost estimates behind most interconnection studies are confidential, the interconnection rates recommended by PwC (2011) based on those costs are similar (\$0.07 per minute) to those recommended on average in Africa (\$0.08 per minute; Lazauskaite (2009)).

7. Simulation

Assumptions. To make simulation tractable, I impose several restrictions:

- Operators cannot charge different prices for on- and off-net calls ($p_t^{F,G} \equiv p_t^{F,G'}$)

[46]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 (the incumbent's fixed cost does not, as it is constant across counterfactuals).

[47]Building a tower costs approximately \$130,000; I consider the total cost of ownership to operate a tower, which includes operating expenses, annualized depreciation, and a 15% cost of capital. Calculated depreciation assumes lifespans of 15 years for towers, 8 years for electric grid access, and 4 years for generators. This results in a total annualized cost of owning and operating a tower in Rwanda of \$51,000 per year, plus \$29,584 for towers that are far from the electric grid that must be powered by generators.

- Consumers may only use one operator each month (single homing)
- Consumers may switch operators at most once

These are feasible rules that could be imposed by a regulator. As a result, my results represent a lower bound of the possible welfare gains from adding a competitor under more general rules.

Method. I take as given the incumbent's initial subscribers and towers, which were a function of its historical choices. Given policy choices $\boldsymbol{f}$, equilibrium index $e \in \{\underline{e}^A, \bar{e}^A\}$, and individual types $\boldsymbol{\eta}$, I identify a subgame perfect equilibrium by in three nested steps:

(1) **Entrant choices**

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

(2) **Incumbent choices**

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

(3) **Consumer choices**

Conditional on firm choices ($\mathbf{p}$ and $\boldsymbol{z}$), I use an iterated best response method to compute a network adoption partial equilibrium:

- *Adoption dates* $\mathbf{x}$: I initialize with a candidate adoption path representing a complete delay of adoption for $\underline{e}^A$ ($\mathbf{x}^0 = \bar{T}$), or immediate adoption for $\bar{e}^A$ ($\mathbf{x}^0 = 0$). I sequentially allow each individual to optimize their adoption date x_i, conditional on the adoption dates of others $\mathbf{x}_{-i}$ and with beliefs about others' operators $\hat{\mathbf{a}}_{-i}(\mathbf{p}, \boldsymbol{\phi}_{-i}, \boldsymbol{\phi}_{median})$, until $\mathbf{x}$ converges.
- *Operators* $\mathbf{a}$*:* Conditional on equilibrium adoption dates $\mathbf{x}$, I initialize with candidate operator choices $\mathbf{a}^0 \equiv A$: all individuals subscribe to operator A. I sequentially allow each individual i to optimize their operator choice $\mathbf{a}_i$, conditional on the actual operators their contacts will use ($\hat{\mathbf{a}}_{-i} = \mathbf{a}_{-i}$), until $\mathbf{a}$ converges.

For the lower equilibrium $\underline{e}^A$, I set individuals' types to their lower bound ($\boldsymbol{\eta} = \underline{\boldsymbol{\eta}}$), and thus will recover a lower bound of the adoption equilibrium. For the upper equilibrium $\bar{e}^A$, I set individuals' types to their upper bound ($\boldsymbol{\eta} = \bar{\boldsymbol{\eta}}$), and thus will recover an upper bound of the adoption equilibrium.[48]

Discussion.

Assumptions. If firms could charge different prices for on- and off-net calls, the number of equilibria proliferates: the entrant favoring equilibrium may have all consumers subscribe to the entrant, and the incumbent favoring equilibrium may have all subscribe to the incumbent. Under those conditions, there would not be enough information to discipline the selection of equilibria. 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 in an attempt to discipline competition.[49]

In markets where different operators have low on-net prices and high off-net prices, it can be common for consumers to hold accounts with multiple operators to connect with others on different networks. Given that I restrict off-network pricing, there is less reason for consumers to hold multiple accounts. For simplicity, I rule out the possibility of multihoming, and switching more than once.

Dark network. If part of the dark network would have become activated prior to $\tilde{T}$, my approach will underestimate demand. I use a later representative survey (RIA, 2012) to model the behavior of the dark network nodes, and report competition results under a shorter horizon under which these nodes would not become active (see Supplemental Appendix).

[48] See Supplemental Appendix for the implementation of the algorithm.

[49] Including Kenya, Singapore, Colombia, Turkey, Slovenia, and Portugal; see TMG (2011).

Computing a single partial equilibrium takes about 15 hours on a high performance computing node, so that computing the roughly 1,800 partial equilibria used in this paper takes approximately 1,125 computer days.[50]

8. Monopoly Benchmarks

Before simulating a competitive equilibrium, I demonstrate how a monopoly model can diagnose how competition may affect the network. I hold fixed individuals' operator choices ($a_{it} \equiv 0$), and trace the impact of prices on welfare, and how the revenue from building rural towers is distributed across the network. I report results under the full horizon of the data (January 2005-May 2009).

Results are shown in Table 3. At baseline, the incumbent's mobile phone system provides net social welfare of $431-483m over this period, an amount equivalent to 3% of Rwandan GDP over the same period.

I refer to lower equilibrium outcomes in the main text (and place upper equilibrium outcomes in parentheses, or omit if the outcomes are identical).

Lowering prices has large welfare benefits. I simulate the equilibria that would result if the monopoly were to lower its price to what it charged after Operator C entered in 2010: an immediate drop in calling prices of 77% (see Figure 2). I assume the firm expands coverage as in the baseline.

As shown in the second row of Table 3, this price reduction would have substantially reduced firm profits, but more than doubled the surplus accruing to consumers. On net, social welfare would have increased by $277m ($272m), which corresponds with 1.6-1.7% of GDP or 8-9% of official development aid over this time period.[51]

[50]To improve computational performance, I reoptimize nodes in parallel, with a synchronized record of all consumers' current choices. A given node is reoptimized only if its conditions or neighbors have changed (breadth first). I use secure computation nodes each with 340GB of RAM and 20 processors, housed at Brown University. I omit computing most of the upper triangular portion of the normal game, which corresponds to the entrant charging higher prices than the incumbent despite having worse coverage: those cells tend to be dominated for the entrant because the vast majority of consumers subscribe to the incumbent.

[51]Since results through T do not include benefits to the dark network, this is represents a lower bound.

Table 3. Benchmark Monopoly Simulations (million $, 2005-5.2009)

	Consumer Surplus	**Gov. Revenue**	**Firm Profits**	**Firm Revenue Breakdown** By Connection			
	All links	All links	All links	Rural-Rural	Rural-Urban	Urban-Rural	Urban-Urban
Baseline	**[244, 270]**	**[65, 73]**	**[122, 140]**	**[30, 33]**	**[17, 18]**	**[24, 28]**	**[95, 108]**
Impact:							
Charge eventual competitive price	**+330, +338**	**-2, -4**	**-51, -62**	**-4, -5**	**-4, -5**	**-1, -4**	**-11, -18**
... only proximal effect	+288, +316	-7, -9	-58, -67	-5, -6	-5, -6	-3, -5	-18, -22
... additional ripple effects	+42, +22	+5, +4	+7, +5	+2, +2	+1, +1	+2, +1	+7, +4
No rural expansion	**-81, -92**	**-11, -14**	**-19, -27**	**-9, -10**	**-4, -4**	**-6. -8**	**-14, -20**
... only proximal effect	-77, -83	-10, -11	-17, -21	-8, -9	-4, -4	-6, -7	-12, -15
... additional ripple effects	-3, -8	-1, -2	-2, -6	-0, -1	-0, -0	-0, -1	-1, -5
Charge eventual competitive price & no rural expansion	**+198, +217**	**-10, -11**	**-56, -66**	**-10, -10**	**-7, -7**	**-5, -7**	**-20, -25**
... only proximal effect	+155, +200	-14, -14	-62, -69	-10, -11	-7, -8	-7, -8	-28, -28
... additional ripple effects	+43, +17	+4, +3	+7, +3	+1, +1	+0, +0	+2, +1	+8, +4

I decompose the effect into the proximal effect: allowing subscribers to individually reoptimize their usage and adoption holding fixed the adoption of others (row 3); and any additional network effects as the impact of these decisions ripple through the network (row 4). 11-19% of the welfare increase comes from network ripple effects, which would not be captured in a standard aggregate demand function.

Investment in rural towers generates network spillovers. Rural areas may be profitable to serve only if one also has a monopoly over urban areas. Under competition, a firm will internalize only a fraction of the potential network effects. Additionally, if firms are not able to charge different prices to rural and urban areas, price pressure in the urban area can lower the revenue earned from rural calls.

I simulate the effects of building full baseline coverage ($\mathbf{z}^0 = \mathbf{z}_{(100\%)}$) relative to a counterfactual where only urban towers are built ($\mathbf{z}^0 = \mathbf{z}_{(0\%)}$; see Figure 3 for coverage maps). I impose the relevant rollout plan, compute corresponding coverage, allow each consumer to adjust their adoption and calling behavior, and compute resulting equilibrium revenues and utility. I compute first the proximal effect, and then any additional network ripple effects.

First, I simulate the impact of removing the full rural expansion, holding prices fixed at the monopoly level. As shown in Table 3, rural-rural links generated only 28% (24%) of the revenue from building rural towers. 31% (29%) of revenue came from links between rural and urban areas. Surprisingly, 44% (48%) of revenue from rural towers came from increased calling along urban-urban links:

- 92% (75%) of urban-urban revenue comes from proximal effects: some urban consumers make calls from rural areas and thus directly benefit from rural coverage (which would be included in their coverage measure ϕ^a_{it}). These consumers create incentives to compete on the quality of rural coverage.
- 8% (25%) of urban-urban revenue comes from network spillover effects, which can result from even consumers who have no desire to call or use rural coverage. These benefits accrue to the interior of the urban network, so would only partially be internalized if that network were split.

The rural expansion was profitable at monopoly prices, but not if prices were reduced to the eventual competitive price, as shown in the final rows of Table 3.

These simulations suggest that competition has the potential for large welfare impacts but may impact investment.

9. Results under Competition

This section presents the results of simulations with competition. I compute results up to horizon 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 monopoly price). Firms are not required to share tower infrastructure but are required to interconnect subscribers. Given that the incumbent had a head start in the market, I report incumbent favoring equilibria in the main text (outcomes under entrant favoring equilibria are reported in the Supplemental Appendix, and are similar).

Figure 4 shows equilibrium outcomes as a function of the interconnection rate (shown decreasing with the x-axis). As the interconnection rate is lowered, price competition becomes more intense (top panel), welfare increases and profits decline (middle panel). Across all interconnection rates, the incumbent would elect to build the rural towers covering the lowest 50% population density locations, but the return on the investment declines as the interconnection rate is lowered (bottom panel). Outcomes are also shown in Table A3.[52]

I find the following:

9.1. **Competition does not develop without government intervention.** In most emerging network goods (and unregulated telecom markets), firms determine the terms of compatibility endogenously. If, prior to the game, the incumbent selects the profit maximizing interconnection rate, it will set it high, beyond the bounds of Figure 4 (f_{ij} = \$0.33).[53] The incumbent and entrant both charge 80% (90%) of the monopoly price, and consumer surplus is only somewhat higher that the monopoly case, as shown in the second row of Table A3.[54] This is similar to many emerging network goods, where one firm is dominant and interconnection does not arise (Katz and Shapiro, 1985).

If the firms coordinated to select an interconnection rate to maximize joint profits, they would select a higher interconnection rate (f_{ij} = \$0.33 (\$0.43)) which induces essentially the same outcomes, shown in the first row of Table A3. This is reminiscent of theoretical results that suggest that if firms select the interconnection rate, they

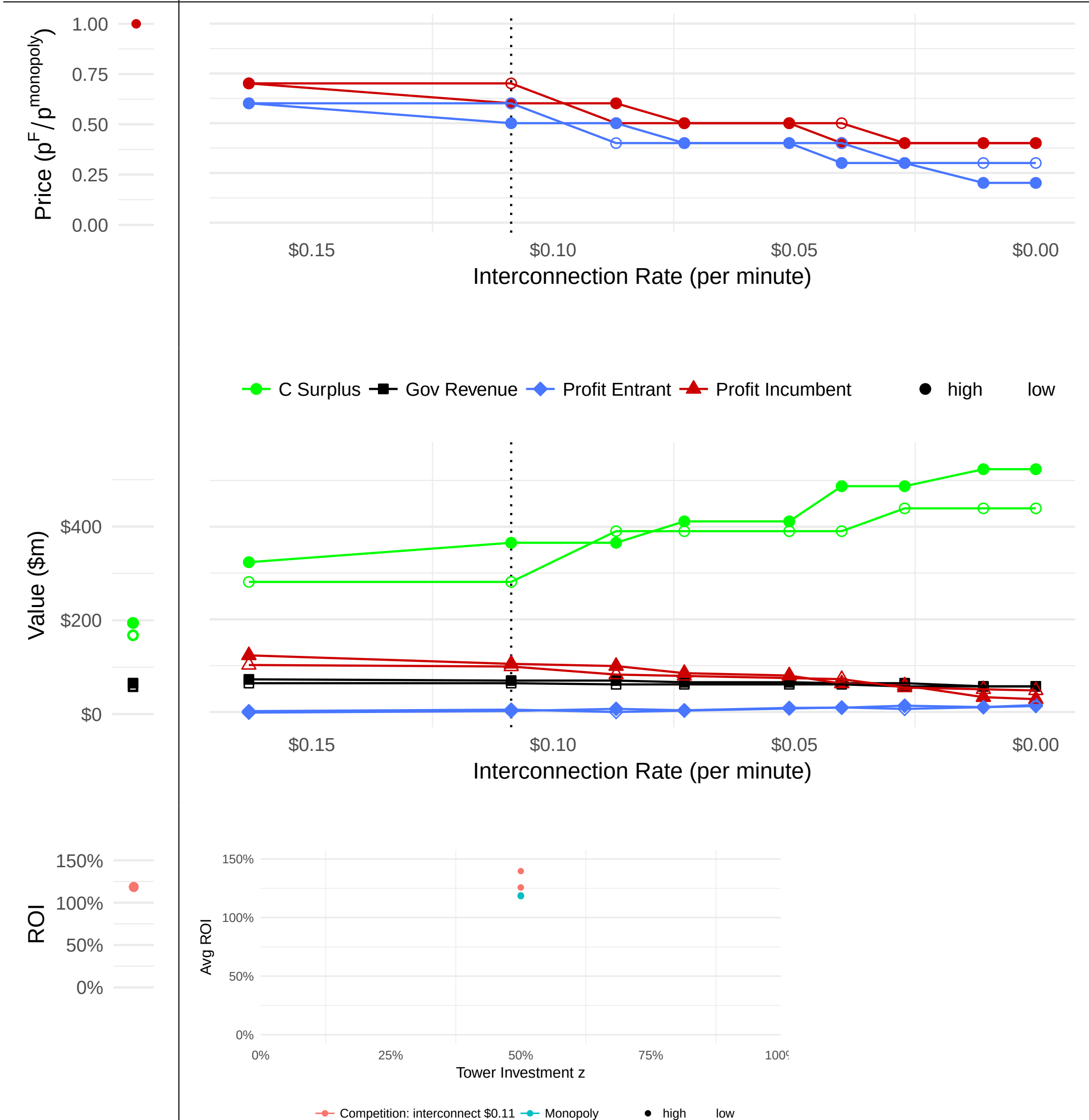
[52]Results tables omit fixed costs, which based on accounting I estimate to lie between \$1-16m for the entrant and are included in welfare estimates in the text. Results also omit license fees, which represent additional transfers to the government. The government charged the entrant \$4m per year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

[53]I allow the incumbent to select the interconnection rate on a grid from \$0.00 to \$0.43.

[54]The entrant is obliged to connect to the incumbent's network, and because of the regulatory restriction that operators charge the same prices for on- and off-net calls, it cannot separately pass through the high cost of interconnection. As a result, the entrant has little advantage to drawing away customers: it pays higher than cost to interconnect with the incumbent's network. (The incumbent earns a higher profit than under monopoly: it captures rents from the entrant, which charges different prices (allowing price discrimination between urban and rural consumers), and for which some consumers have idiosyncratic preferences.)

FIGURE 4. Equilibrium Results as Function of Interconnection Rate

Baseline	Counterfactual
	Holding Rollout Plans Fixed
Monopoly	**Additional Competitor**



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. Equilibrium with entrant moving first, and consumers favoring incumbent.

may use it as an instrument of collusion to sustain high prices (Armstrong, 1998; Laffont et al., 1998).

9.2. **Increasing compatibility lowers prices and incentives to invest.**

9.3. **Competition can lower prices and *increase* incentives to invest.** If the government selects the interconnection rate, it can choose a level that lowers prices, *increases* incentives to invest, and dramatically improves welfare. This focal level of f_{ij} = \$0.11 is highlighted in a dotted line in Figure 4, which would induce the incumbent to reduce prices to 70% (60%) of the monopoly price, and the entrant to 60% (50%) of the monopoly price. Outcomes are shown in the third row of Table A3, and the price series is shown in Figure 2.[55] This policy change would have had an enormous impact on welfare. Over the horizon from 2005-2008, at baseline the monopoly provided a social surplus of \$334m (\$386m), an amount equivalent to 2-3% of Rwanda's GDP over the same time period. Adding a competitor under this interconnection rate would increase net social welfare by \$109m (\$147m), an amount equivalent to 1% of GDP or 3-5% of official development aid in Rwanda over the same period.[56]

Demand for the entrant is much more elastic in price, given its lower quality. Around this focal equilibrium, the own price elasticity of duration for the entrant is -1.00, versus for the incumbent -0.40 (-0.39).[57] If the entrant marginally increased its price, of the resulting change in duration, 97% would be diverted to the incumbent; the remaining 3% of call duration would not be placed. In contrast, if the incumbent marginally increased its price, 82% (86%) of the change in duration would be diverted to the entrant. This diversion ratio differs substantially based on the location of subscribers. For urban consumers, 85% (91%) of duration would divert to the entrant, which is a close substitute. For rural consumers, only 57% (60%) would divert to the entrant, which offers poor rural coverage. (For more on diversion ratios see Conlon and Mortimer (2018).)

[55] Tables A1 and A2 show the resulting normal form games.

[56] 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.

[57] The cross price elasticities are 0.14 (0.30) and 2.33 (1.09), respectively. Statistics computed by measuring how demand shifts when the selected firm's price is perturbed from the equilibrium price by 10 percentage points of the monopoly price.

This focal interconnection rate is slightly higher than the level the regulator used at that time ($f_{ij} = \$0.09$), or was recommended based on the consultant report (PwC, 2011) of ($f_{ij} = \$0.07$). It is also higher than the zero rated interconnection rate ($f_{ij} = \$0$: 'bill and keep', to which the U.S. is transitioning (FCC, 2011)). As shown in both Figures 4 and Table A3, these lower interconnection rates would result in lower prices and higher welfare. While the incumbent would still make the rural tower investment under these lower interconnection rates, it would earn a lower return than under monopoly.

Incentives to invest are driven by business stealing. To better understand the investment effects, I simulate adoption partial equilibria where tower investments are removed. I first consider the focal interconnection rate ($f_{ij} = \$0.11$). Table 4 decomposes the three effects outlined in Section 2:

1. Competition lowers overall revenues. Under competition, prices are lower so each second of talk time generates less revenue. Under monopoly, building these towers generated total revenue of \$2.57m (\$2.46m), but under competition it generated net revenue of \$1.52m (\$1.51m) combined between the two operators. This is shown in the first two rows of Table 4.

2. Under competition, some of the network effects from an investment are foregone. Under monopoly, 100% of the revenues from investing accrue to the incumbent, as shown in the first row of Table 4.

However, when the incumbent faces a competing network, it captures only 93% (88%) of the revenue when operator choices are held fixed, as shown in the third row of Table 4. Due to network effects, the remaining 7% (12%) of revenue results from network effects spilling over into its competitor's network. The majority, 6% (11%), accrues to the entrant at the network border (entrant's off-net calls). These spillovers can partially be recouped with interconnection fees: 4% (9%) of total revenue is given back.[58] However, 1% (0.2%) of the revenue results from spillovers in the interior of

[58]Note that theoretically, there can be cases where competition *increases* revenues from this channel: if operators are sufficiently differentiated that the entrant attracts consumers who would not have

the entrant's network (entrant on-net calls). Since interconnection fees are incurred only at the boundaries of the two networks, they do not adjust for these internal spillovers. In this case, foregone network effects are relatively small.[59]

On net, effects 1 and 2 lower the private ROI from 0.98 (1.00) under monopoly to 0.43 (0.25) under competition without the potential for business stealing.

3. A business stealing effect increases the incentive to differentiate quality. However, competition introduces a new motive to invest: investing may induce marginal consumers to switch networks. The fourth row of Table 4 quantifies the additional effect when consumers are allowed to change operators. This business stealing effect accounts for 64% (70%) of the revenue the incumbent earns from the investment, dwarfing the foregone network effects. As a result the incumbent's ROI of building these towers rises to 1.40 (1.26): larger than the returns under monopoly. Figure 5 shows that building these towers induces urban consumers who spend a fraction of their time in rural areas to switch networks.

Discussion. Whether competition increases or decreases incentives to invest depends on several factors.

First, it depends on the competition policy. If the government implemented an interconnection rate of zero ('bill and keep'), more intense competition leads to lower prices, and the incumbent does not earn interconnection fees for the benefits it provides to the other network. As shown in the last three rows of Table 4, the private ROI decreases below the monopoly level to 0.56 (0.79).

Second, it also depends on the potential size of a business stealing effect. This depends on how the investment interacts with consumer preferences, which can be diagnosed directly.

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adopted under the incumbent, and interconnection fees are large enough. However, in this case, the entrant offers an inferior service that is not sufficiently differentiated.

[59]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.

Consider an alternate case where consumers did not travel, so that rural consumers could only use a network if it provided rural coverage, and urban consumers valued only urban coverage. Then, the incumbent would be the only option for rural consumers, but urban consumers would not switch operators based on rural coverage. In that case there would be no business stealing effect, and competition would tend to lower incentives to invest in towers.

The monopoly benchmark simulations presented in Section 8 foreshadow that in the Rwandan mobile phone network, the business stealing effect is likely to be large. A large portion of revenue generated by rural towers comes from urban consumers who value and use rural coverage, for whom coverage could become a competitive differentiator. Such diagnostic simulations can be computed even in settings where later entry is not observed.

For example, policymakers are considering using competition to discipline social media networks, to address perceived problems of addictiveness or the proliferation of false information. However, if consumers enjoy addictive designs or consuming fake news, then they are unlikely to switch to a competing network that is less addictive or better monitored. In such an environment, competition is likely to reduce the investments of interest (though it may increase other investments).

Additional Results.

Asymmetric interconnection rates give regulators finer control. A regulator may wish to impose asymmetric interconnection rates for two reasons. The regulator could tilt favor towards a smaller network by allowing it discounted access to the larger network. Or in contrast, a regulator may wish to allow a larger network to charge a higher rate to offset foregone network effects from investment. The sixth and seventh rows of Table A3 demonstrate results under asymmetric interconnection rates. Switching the direction of the discount between incumbent and entrant can sway prices by as much as 30 percent of the monopoly price, and consumer surplus by \$159m (\$122m).

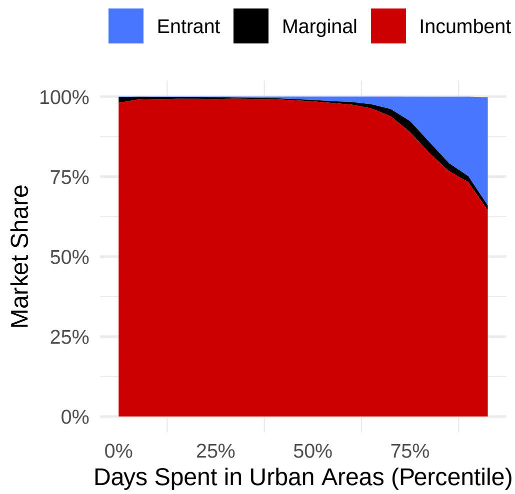
TABLE 4. Return on Tower Investments under Different Competition Policies

	Equilibrium		Impact of Investment							ROI	
	Prices		Incumbent			Interconnect	Entrant				
	Incumb.	Entrant	Costs	Revenue		Fees	Revenue		Costs		
	$\frac{\mathbf{p}^0}{\mathbf{p}^{mono}}$	$\frac{\mathbf{p}^1}{\mathbf{p}^{mono}}$		On-net	Off-net calls	←	Off-net calls	On-net		Private	Social
			\$m	\$m	\$m	\$m	\$m	\$m	\$m		
<u>**Impact of building lowest population density towers**</u>											
Baseline monopoly	**1.00, 1.00**	-	**1.30, 1.23**	**2.57, 2.46**	**0, 0**	-	-	-	-	**0.98, 1.00**	**6.64, 6.49**
With competitor, interconnection \$0.11/min	**0.70, 0.60**	**0.60, 0.50**	**1.42, 1.49**	**4.89, 4.69**	**-1.39, -1.38**	**-0.08, 0.05**	**-1.32, -1.13**	**-0.58, -0.72**	**-0.55, -0.64**	**1.40, 1.26**	**7.74, 7.96**
...fixing operator			0.92, 0.88	1.23, 0.97	0.03, 0.03	0.05, 0.10	0.08, 0.13	0.01, 0.002	0.02, 0.03	0.43, 0.25	6.89, 6.92
...additional effect of operator choice			0.51, 0.61	3.66, 3.72	-1.42, -1.41	-0.13, -0.05	-1.40, -1.26	-0.59, -0.72	-0.57, -0.67	-	-
With competitor, interconnection \$0	**0.40, 0.40**	**0.30, 0.20**	**1.56, 3.57**	**3.47, 6.66**	**-1.03, -0.27**	**0, 0**	**-0.72, 1.19**	**-0.55, -4.31**	**-0.72, -2.86**	**0.56, 0.79**	**8.01, 10.45**
...fixing operator			0.89, 0.78	0.68, 0.43	0.02, 0.06	0, 0	0.08, 0.07	0.002, 0.02	0.03, 0.06	-0.21, -0.37	6.90, 5.99
...additional effect of operator choice			0.67, 2.79	2.79, 6.22	-1.05, -0.33	0, 0	-0.81, 1,11	-0.55, -4.32	-0.75, -2.92	-	-

In outcome cells, first number is outcome in low equilibrium; second in high. Outcomes computed from January 2005 through horizon December 2008. When holding operator choices fixed, consumers who initially switched operators are allowed to change their adoption date for the initial operator but maintain the same switch date. On-net revenues include revenue from extra fees. Interconnect fees represent net payment from entrant to incumbent. Social ROI represents consumer surplus, government revenue, and firm profit, relative to firm costs. ROI is relevant for the total effect of building towers, and the effect of building towers when operator choice is held fixed, but not for the incremental effect of allowing operator choice since the cost of the towers has already been accounted for.

FIGURE 5. Effects of Investment

(a) 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, it induces the highlighted marginal group of users to switch from the entrant to the incumbent (changing the rollout plan from $\mathbf{z}_{(50\%)}$ to $\mathbf{z}_{(100\%)}$). These marginal users are mostly urban but place some calls from affected rural locations. Interconnection rate \$0.11/min, low equilibrium, incumbent favoring (high equilibrium is visually indistinguishable).

Number portability increases the level of competition. Switching costs have theoretically ambiguous effects on network competition (Farrell and Shapiro, 1988; Suleymanova and Wey, 2011; Chen, 2016). For telecom, a major policy under consideration is whether consumers should be able to port their phone numbers from one operator to another: in 2013, 25% of developing markets had introduced number portability and 15% were planning to do so in the future (GSMA, 2013).[60] I simulate the effect of introducing number portability in the second to last row of Table A3, by reducing the cost of switching operators from \$36.09 to \$18.51 (based on my consumer survey estimates). This results in more intense price competition in the lower equilibrium, which lowers incumbent profits relative to competition without number portability. This suggests that if given the choice, the incumbent would elect to maintain high

[60]31% of Rwandans state that they would have switched operators if they could keep their phone number (Stork and Stork, 2008). Rwanda initially planned to introduce portability when mobile operators reached combined 60% market penetration, but as of this writing has yet to do so.

switching costs. The policy results boosts in consumer surplus, by different amounts in the low and high equilibria: +\$159m (+\$1m).[61]

Robustness. In the baseline case, the government eventually allowed Operator C to enter (in the end of 2009). If I similarly delay the entry of the competitor until July 2008 (5 months before the end of the horizon), the impact on prices and welfare is muted.[62] Outcomes are shown in the bottom of Table A3. Relative to early entry, the entrant sets lower prices (40% (30%) of the monopoly level), the incumbent keeps prices weakly higher (70% of the monopoly level), and the total impact on welfare is smaller.

The Supplemental Appendix assesses several alternate specifications. Results under entrant favoring equilibria are very similar. Results are similar under different time horizons, including a longer horizon through period T with that final period then repeated for 3 years. Results are similar under different draws of the random preferences $[\underline{\eta}_i^1, \bar{\eta}_i^1]$. If the incumbent moves before the entrant, results are similar, but are less stable for the grid of prices I consider. If at the point of adoption, consumers exactly anticipate which operators their contacts will select ($\hat{\mathbf{a}}_j = \mathbf{a}_j$), consumer decisions are no longer guaranteed to reach equilibrium, but the approximate equilibria they reach have very similar outcomes.

10. 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 provide the infrastructure for an increasing array of vital services, including communication and increasingly payments and banking. I demonstrate how data from an incumbent monopoly can be used to estimate the effects of a variety of competition policies. My method captures how changes ripple throughout networks and across

[61]This large distinction between the two equilibria would likely to be muted if prices were evaluated on a finer grid.

[62]Before the entry date, subscribers may select only the incumbent ($a_{it} \equiv 0$ for $t < t_{entry}$); after that date, they may select either ($a_{it} \in \{0, 1\}$ for $t \geq t_{entry}$).

network boundaries, and can thus decompose how the policy environment affects incentives to invest. In addition to the policies demonstrated here, this method can also estimate effect of splitting up an incumbent, under arbitrary splits of customers and assets.

I find that competition in the Rwandan mobile phone industry has a large scope to affect welfare. I find that 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. 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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Coverage	IncumbentPrice	10pct	20pct	30pct	40pct	50pct	60pct	70pct	80pct	90pct	Full
Build all towers	10pct	-23, -1	-22, -2	-22, -2	-22, -2	-22, -2	-22, -2	-22, -2	-22, -2	-22, -2	-22, -2
Build all towers	20pct	39, -37	17, -1	18, -2	18, -2	18, -2	18, -2	18, -2	18, -2	18, -2	18, -2
Build all towers	30pct	**56**, -52	61, -25	45, -1	45, -2	45, -2	45, -2	45, -2	45, -2	45, -2	45, -2
Build all towers	40pct	51, -53	**66**, -28	**71**, -12	69, -1	69, -2	69, -2	69, -2	69, -2	69, -2	69, -2
Build all towers	50pct	38, -45	53, -22	69, -9	**85**, -5	88, -1	89, -2	89, -2	89, -2	89, -2	89, -2
Build all towers	60pct	30, -41	40, -14	54, -1	76, 5	**91**, 2	97, -2	97, -2	97, -2	97, -2	97, -2
Build all towers	70pct	24, -38	31, -8	40, 8	57, 17	77, 13	**98**, 5	**107**, -2	107, -2	107, -2	107, -2
Build all towers	80pct	19, -35	24, -4	30, 14	41, 27	55, 28	78, 20	101, 6	**110**, -2	**111**, -2	
Build all towers	90pct	15, -34	18, -1	23, 19	30, 35	39, 38	53, 36	78, 24	103, 5	110, -2	**110**, -2
Build all towers	Full	12, -33	14, 1	17, 22	23, 39	28, 47	37, 47	51, 41	76, 25	101, 5	108, -2
Don't build last 34 rural towers	10pct	-22, -1		-22, -2							
Don't build last 34 rural towers	20pct	39, -38	18, -1								
Don't build last 34 rural towers	30pct	52, -50	60, -25	45, -1							
Don't build last 34 rural towers	40pct	45, -51	60, -25	71, -12	69, -1						
Don't build last 34 rural towers	50pct	32, -43	48, -21	64, -6	84, -4	88, -1					
Don't build last 34 rural towers	60pct	23, -38	33, -11	48, 2	70, 8	88, 3	97, -1				
Don't build last 34 rural towers	70pct	17, -35	23, -5	34, 11	50, 20	70, 18	96, 6	106, -2			
Don't build last 34 rural towers	80pct	13, -33	17, -1	23, 18	34, 32	48, 32	71, 25	99, 7	110, -2		
Don't build last 34 rural towers	90pct	10, -32	12, 1	16, 23	23, 39	32, 43	46, 40	70, 29	100, 7	109, -2	
Don't build last 34 rural towers	Full	8, -32	10, 2	11, 25	15, 44	21, 51	30, 51	44, 46	68, 31	98, 6	107, -2

Incumbent actions in rows; entrant price in columns. Cells represent incumbent and entrant profits respectively, in million USD. Best responses are bolded. Underlined cell represents a subgame perfect equilibrium when the entrant moves first.

TABLE A1. Competitive Interaction: Interconnection $0.11 Switching Cost $36 Low Equilibrium -200812 (50pct dark) First Mover Entrant Favor Incumbent

Coverage	IncumbentPrice	10pct	20pct	30pct	40pct	50pct	60pct	70pct	80pct	90pct	Full
Build all towers	10pct	-22, -1	-22, -2	-22, -2	-22, -2	-22, -2	-22, -2	-22, -2	-22, -2	-22, -2	-22, -2
Build all towers	20pct	42, -40	20, -1	20, -2	20, -2	20, -2	20, -2	20, -2	20, -2	20, -2	20, -2
Build all towers	30pct	**60**, -54	68, -28	55, -1	55, -2	55, -2	55, -2	55, -2	55, -2	55, -2	55, -2
Build all towers	40pct	53, -55	**72**, -29	**84**, -13	78, -1	78, -2	78, -2	78, -2	78, -2	78, -2	78, -2
Build all towers	50pct	41, -47	58, -22	79, -7	**92**, -5	97, -1	97, -2	97, -2	97, -2	97, -2	97, -2
Build all towers	60pct	32, -43	43, -13	61, 4	82, 5	<u>**104**, 2</u>	**114**, -2	115, -2	115, -2	115, -2	115, -2
Build all towers	70pct	26, -39	33, -7	44, 15	60, 19	87, 17	113, 8	**123**, -2	123, -2	123, -2	123, -2
Build all towers	80pct	20, -37	26, -3	33, 22	44, 31	62, 35	92, 26	113, 9	**127**, -2	127, -2	
Build all towers	90pct	16, -35	20, 0	25, 26	32, 39	44, 47	63, 47	89, 29	116, 9	**128**, -2	**128**, -2
Build all towers	Full	13, -34	16, 2	19, 30	24, 44	32, 56	44, 60	60, 50	86, 31	116, 7	126, -1
Don't build last 34 rural towers	10pct	-22, -1		-21, -2		-21, -2		-21, -2		-21, -2	-21, -2
Don't build last 34 rural towers	20pct	43, -40	21, -1								
Don't build last 34 rural towers	30pct	56, -53	67, -27	56, -1		56, -2		56, -2		56, -2	56, -2
Don't build last 34 rural towers	40pct	48, -53	66, -26	83, -12	78, -1						
Don't build last 34 rural towers	50pct	34, -45	52, -21	73, -4	91, -4	97, -1		97, -2		97, -2	97, -2
Don't build last 34 rural towers	60pct	24, -39	36, -9	54, 7	76, 10	102, 3	114, -1				
Don't build last 34 rural towers	70pct	18, -37	25, -3	36, 19	53, 23	80, 22	111, 9	122, -2		122, -2	122, -2
Don't build last 34 rural towers	80pct	14, -35	18, 1	25, 27	36, 35	54, 40	84, 32	111, 10	126, -2		
Don't build last 34 rural towers	90pct	11, -34	14, 3	17, 30	24, 44	36, 53	55, 52	81, 35	113, 10	127, -2	127, -2
Don't build last 34 rural towers	Full	9, -33	10, 5	13, 33	16, 49	24, 62	36, 66	51, 56	78, 37	114, 9	125, -2

Incumbent actions in rows; entrant price in columns. Cells represent incumbent and entrant profits respectively, in million USD. Best responses are bolded. Underlined cell represents a subgame perfect equilibrium when the entrant moves first.

TABLE A2. Competitive Interaction: Interconnection $0.11 Switching Cost $36 High Equilibrium -200812 (50pct dark) First Mover Entrant Favor Incumbent

Table A3. Impact of Adding Competitor under Different Rules

Policy	Inter-connect f_{ij} $/min	Switch. Cost s $	Prices $\frac{\mathbf{p}^0}{\mathbf{p}^{mono}}$	$\frac{\mathbf{p}^1}{\mathbf{p}^{mono}}$	Incumbent Profit $m	Entrant Profit $m	Gov. Revenue $m	C. Surplus $m
Baseline Monopoly	-	-	1.00, 1.00	-	[108, 126]	[0, 0]	[58, 66]	[168, 194]
Impact of adding additional competitor						**Change:**		
Entering January 2005								
Interconnection rate								
...joint profit maximizing	0.33, 0.43 $\leftrightarrow$	36	0.80, 0.90	0.80, 0.90	1, 2	-1, -1	4, 2	69, 32
...inc. profit maximizing	0.33 $\leftrightarrow$	36	0.80, 0.90	0.80, 0.90	2, 1	-1, -1	4, 2	69, 32
...focal	0.11 $\leftrightarrow$	36	0.70, 0.60	0.60, 0.50	-10, -23	5, 2	4, 2	113, 171
...initial level (RURA, 2006)	0.09 $\leftrightarrow$	36	0.50, 0.60	0.40, 0.50	-28, -27	-0, 7	1, 2	222, 171
...revised level (PwC, 2011)	0.07 $\leftrightarrow$	36	0.50, 0.50	0.40, 0.40	-31, -43	3, 4	1, -2	222, 217
...bill and keep	0.00 $\leftrightarrow$	36	0.40, 0.40	0.30, 0.20	-62, -99	13, 15	-3, -11	272, 330
...asymmetric: to incumbent	0.04 $\leftarrow$	36	0.40, 0.40	0.30, 0.30	-55, -68	6, 12	-3, -4	272, 293
to entrant	0.07 $\rightarrow$							
...asymmetric: to incumbent	0.07 $\leftarrow$	36	0.70, 0.60	0.60, 0.50	-10, -28	5, 7	4, 2	113, 171
to entrant	0.04 $\rightarrow$							
Interconnection rate focal + number portability	0.11 $\leftrightarrow$	19	0.50, 0.60	0.50, 0.50	-20, -26	-1, 5	3, 2	215, 172
Entering July 2008								
...focal	0.11 $\leftrightarrow$	36	0.70, 0.70	0.40, 0.30	-11, -18	2, 2	1, -1	91, 90

Outcomes (January 2005-December 2008).

In outcome cells, first number is low equilibrium; second is high, for the incumbent favoring equilibrium. First row presents baseline outcomes; following rows represent the change from this baseline. Profits omit fixed costs of operation and license fees. $\leftrightarrow$ indicates symmetric interconnection rate; $\leftarrow$ indicates rate charged to entrant for connecting to incumbent; $\rightarrow$ indicates rate charged to incumbent for connecting to entrant. Revised level corresponds to start of glide path recommended by (PwC, 2011).

Appendix A. Estimation under Monopoly

Identification. Traditional approaches towards network goods estimate the value of each connection indirectly, based on correlations in adoption. For example, consider individual i who has one link, does not consider the future ($\delta = 0$), and is deciding whether to adopt, $A_i \in \{0, 1\}$. i will adopt if the value exceeds the cost:

$$A_i = I\left(\theta_{ij} A_j + \eta_i^0 \geq p_t^{handset}\right)$$

where θ_{ij} is the value of the link if j also adopts. It is difficult to estimate θ_{ij} from correlations in adoption: each individual's adoption depends on the other's, as well as any unobserved shocks, which are likely to be correlated (Manski, 1993). Approaches that instrument for adoption tend to rely on very particular variation, and yield crude measures of value.[63]

Rather than inferring θ_{ij} from correlated adoption, I measure it directly. A link provides value because it enables calls:

$$\theta_{ij} = Eu_{ij}(p_t^0, \boldsymbol{\phi}_t^0)$$

I identify a link's value by how its usage changes in response to changes in the cost of communicating. The value of all links together represent the value of the network.

My approach requires that the latent desire to communicate (ϵ_{ijt}) is uncorrelated with costs (p_t^0 and $\phi_{it}^0 \phi_{jt}^0$, which both improve over time). As the network grows, the composition of subscribers changes, and the operator may adjust prices and coverage in response. I absorb compositional changes by using only within-link variation to estimate the response of usage to costs. My identification assumption implies that the value of communicating with a particular contact does not otherwise trend over time, or depend on who else has adopted. I test this assumption by analyzing changes in calling patterns across links; results are consistent with these factors being negligible.[64] Apart from these restrictions, communication shocks can be arbitrarily correlated between any links in the network.

[63]For example, Tucker (2008) identifies the value of a videoconferencing system using variation in television watching partly driven by the World Cup. Instrumental variable approaches do not capture rich heterogeneity, or account for how the cost of using a link affects its value.

[64]I evaluate whether the duration of calls across a link changes with the time since an individual adopted, or as more of the sender's and receiver's contacts join the network, after controlling for cost. For the median subscriber, the change in duration associated with either time, or the change in the number of that individual's contacts on the network is less than 5% of the change associated with the changes in prices and coverage over this time period. See Supplemental Appendix.

After the network portion of utility (θ_{ij}) is estimated, it is straightforward to back out any residual heterogeneity affecting adoption, η_i^0. These types may be arbitrarily correlated between nodes, but are fixed over time and across counterfactuals.

Call decision. Call decisions reveal the country's latent communication graph (the call shock distributions F_{ij}), the shape of the utility function (γ and α), and how usage responds to cost (β_{cost} and $\beta_{coverage}$). I allow the call shock distributions to vary at the link level $\epsilon_{ijt} \overset{iid}{\sim} F(\sigma_i, q_i, \mu_{ij})$ (an analogue of link fixed effects), so that the response of usage to cost is identified within-link (how does usage across a given link change as prices and coverage change). I specify the distribution for call shocks $\epsilon_{ijt} \overset{iid}{\sim} F_{ij}$ as a mixture distribution:

$$F_{ij}\left[\epsilon_{ijt}\right] = q_i \Phi\left(\frac{\ln\left(\epsilon_{ijt}\right) - \mu_{ij}}{\sigma_i}\right) + (1 - q_i) 1_{\{\epsilon_{ijt} > -\infty\}}$$

where $\Phi(\cdot)$ represents the standard normal CDF. The first component is a log-normal distribution, $\ln N(\mu_{ij}, \sigma_i^2)$, which captures a continuous spread of potential communication. It suggests that an individual will not call across a link if the shock is too low relative to the cost (affected by α in the utility function). However, across some links one would observe no calls even if calling were free. To rationalize the large fraction of months that have no calls across each link, I also include a point mass, under which there are no calls regardless of the cost (controlled by the individual parameter q_i).

In each period t, for each link between subscribers, I observe a duration $d_{ijt} \geq 0$. Equation 2 recovers the underlying call shock ϵ:

$$\epsilon\left(d, p_t, \phi_{it}, \phi_{jt}\right) = \frac{d^{\gamma-1} + \alpha}{1 - \beta_{cost}\left(p_t + \beta_{coverage}\phi_{it}\phi_{jt}\right)}$$

given coverage under the baseline rollout plan $\boldsymbol{\phi}_t(\mathbf{z}_0)$. If the call shock was not high enough to place a call of at least one second, the month will have no call ($d_{ijt} = 0$), with likelihood $F_{ij}\left[\epsilon\left(1 \text{ second}, \ldots\right)\right]$. The likelihood of calls of total duration d_{ijt} is $F_{ij}\left[\epsilon\left(d_{ijt} + 1, \ldots\right)\right] - F_{ij}\left[\epsilon\left(d_{ijt}, \ldots\right)\right]$.

These are combined into the log-likelihood function:

$$\ln L(\Theta) = \sum_i \sum_t \sum_{j \in S_t \cap G_i} \quad 1_{\{\text{call placed}_{ijt}\}} \ln \left(F_{ij} \left[\epsilon \left(d_{ijt} + 1, p_t, \phi_{it}, \phi_{jt} \right) \right] - F_{ij} \left[\epsilon \left(d_{ijt}, p_t, \phi_{it}, \phi_{jt} \right) \right] \right) + \left[1 - 1_{\{\text{call placed}_{ijt}\}} \right] \ln F_{ij} \left[\epsilon \left(1 \text{ second}, p_t, \phi_{it}, \phi_{jt} \right) \right]$$

The full sample has 1,525,061 nodes, 414.5 million links, and a total of 15 billion link-month duration observations. The calling decision has 7 types of parameters. I assume that the shape and sensitivity parameters are common to all links (γ, α, β_{cost}, $\beta_{coverage}$). I allow the parameter scaling the shock distribution (σ_i), and the probability of no call at any price ($1 - q_i$) to vary at the individual level. I allow the shock distribution to be shifted at the link level to ensure that price and coverage sensitivity are identified off of within-link changes in calling.[65]

Björkegren (2019) uses a two step maximum likelihood procedure to estimate all 4.6 million parameters, exploiting the fact that conditional on the common parameters and cost fixed effects, an individual's distribution parameters affect only his own likelihood.

Adoption decision. The adoption decision bounds an individual's type under the incumbent, η_i^0. Consider the utility i would have received had he adopted a different month. At time x_i, i bought a handset rather than waiting K months. Holding fixed the actions of others, Equation 6 implies $E_{x_i} U_i^{0,x_i}(\boldsymbol{x}_{G_i}, \mathbf{0}) \geq E_{x_i} U_i^{0,x_i+K}(\boldsymbol{x}_{G_i}, \mathbf{0})$. This implies that the expected utility of being on the network during the following K months must have exceeded the expected drop in handset prices:[66]

$$\text{(7)} \qquad \sum_{s=0}^{K-1} \delta^s E u_{ix_i+s}(p_{x_i+s}, \boldsymbol{\phi}_{x_i+s}, \boldsymbol{x}_{G_i}, \mathbf{0}) + (1 - \delta^K)\eta_i^0 \geq p_{x_i}^{handset} - \delta^K E_{x_i} p_{x_i+K}^{handset}$$

Similarly, i could have purchased a handset earlier. At time $x_i - K$, i chose to wait, so he must have preferred some future adoption date: for some $\tilde{K} > 0$, $E_{x_i-K} U_i^{0,x_i-K+\tilde{K}}(\boldsymbol{x}_{G_i}, \mathbf{0}) \geq$

[65] I define $\mu_{ij} = \mu_i + \mu_{\max(x_i,x_j),\overline{\phi_{it}\phi_{jt}}}$, which includes an individual mean term μ_i, and a cost fixed effect for each combination of link adoption date ($\max\{x_i, x_j\}$) and average coverage ($\overline{\phi_{it}\phi_{jt}}$), discretized to 519 combinations. See Björkegren (2019).

[66] The model implies that i correctly forecasts the first K months of utility and his expectation of the continuation flow does not change between x_i and $x_i + K$. Both options provide the same continuation flow of utility after $x_i + K$, so they differ only in the utility provided in the first K months.

$E_{x_i-K}U_i^{0,x_i-K}(\boldsymbol{x}_{G_i},\mathbf{0})$. He must have valued those $\tilde{K}$ months of expected utility less than the expected drop in handset prices:

(8)
$$\sum_{s=0}^{\tilde{K}-1}\delta^s Eu_{i,x_i-K+s}(p_{x_i-K+s},\boldsymbol{\phi}_{x_i-K+s},\boldsymbol{x}_{G_i},\mathbf{0})+(1-\delta^{\tilde{K}})\eta_i^0 \leq p^{handset}_{x_i-K}-\delta^{\tilde{K}}E_{x_i-K}p^{handset}_{x_i-K+\tilde{K}}$$

These inequalities imply bounds for each individual's type under the incumbent: $\underline{\eta}_i^0 \leq \eta_i^0 \leq \bar{\eta}_i^0$, where:

(9)
$$\underline{\eta}_i^0 = \frac{1}{1-\delta^K}\left[p^{handset}_{x_i}-\delta^K E_{x_i}p^{handset}_{x_i+K}-\sum_{s=0}^{K-1}\delta^s Eu_{i,x_i+s}(p_{x_i+s},\boldsymbol{\phi}_{x_i+s},\boldsymbol{x}_{Gi},\mathbf{0})\right]$$
$$\bar{\eta}_i^0 = \max_{\tilde{K}>0}\left[\frac{1}{1-\delta^{\tilde{K}}}\left[p^{handset}_{x_i-K}-\delta^{\tilde{K}}E_{x_i-K}p^{handset}_{x_i-K+\tilde{K}}-\sum_{s=0}^{\tilde{K}-1}\delta^s Eu_{i,x_i-K+s}(p_{x_i-K+s},\boldsymbol{\phi}_{x_i-K+s},\boldsymbol{x}_{Gi},\mathbf{0})\right]\right]$$

I set $K = 2$ months.[67] Note that the future after $x_i + \max(K, \tilde{K} - K)$ cancels out of these expressions: as long as the next preferred adoption date occurs within the data, results are not sensitive to the evolution of the network beyond that point. These conditions are necessary for equilibrium and are valid in the presence of multiple equilibria. During months that extra fees were charged, I incorporate the fee schedule.[68] I set the discount factor to the inverse of the average real interest rate in Rwanda over this period: $\delta = (\frac{1}{1.07})^{1/12} \sim 0.9945$ (source: World Bank). I am able to recover η_i^0's for 0.8m nodes adopting between $x_i \in [K, T-K]$.[69]

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[67]I select K to balance two forces: lower values produce tighter bounds; higher ones smooth any shocks around their adoption date that are unaccounted for.

[68]Before June 2007, subscribers needed to add roughly \$4.53 in credit per month to keep their account open; I factor this in as a hassle cost. The operator removed this minimum as part of a series of price reductions. Actually opening an account entails purchasing a SIM card, which cost roughly \$1 itself plus the cost of an initial top up. See Supplemental Appendix of Björkegren (2019).

[69]I do not back out bounds for roughly 40,000 individuals receiving a rural handset subsidy in 2008 (for whom it is difficult to value the purchase), and whose activation does not coincide with the adoption of a new handset (altogether these account for 5% of last period durations). In simulations, I compute changes in the call model for all nodes, and hold the adoption of these fixed; doing so will tend to attenuate the results of policy counterfactuals.

Validation. In a robustness check, Björkegren (2019) finds that the value implied by calls corresponds with the value implied by adoption, using moment inequalities analogous to Equations 7 and 8.[70]

[70] See Supplemental Appendix for more details.