This paper evaluates whether competition hinders or spurs investment in a network industry. When a network is split between competitors, potential network effects are foregone. However, a firm may invest in components that are not shared, to steal customers from its competitors. 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.

**JEL Classification Codes:** O33, L96, O180, L51

**Keywords:** network effects, infrastructure, information technology
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.\footnote{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.” \cite{Kimball2019}}

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.\footnote{Voice accounts for 60% of the my telecom partner’s parent’s African revenue in 2017 (including two small operations outside of Africa).} The details of how to manage competition have been ‘a main bottleneck’ \cite{WorldBank2004}, and regulators have little guidance on when to tilt favor, allow consolidation \cite{Moody2015}, or split firms \cite{Reuters2017}.

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. While there is substantial theory, conclusions depend on empirical parameters. 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.

A straightforward reduced form approach, like Faccio and Zingales (2017) and Genakos et al. (2018), compares isolated networks in jurisdictions that set different policies. They 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. 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.

A structural model could instead be used to evaluate an entire spectrum of policy options, under expectations that can be specified. 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. Second, it is difficult to identify network effects, because each individual’s demand is a function of

---

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 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 is unable to find significant quality differences between countries with different policies.

7 I am not aware of any studies that have linked network usage data from multiple competing networks.
the demand of others in the network. One individual may adopt after a contact adopts because the contact provides network benefits, or because connected individuals share similar traits or are exposed to similar environments. 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, using 5.3 billion transaction records from the incumbent mobile phone operator which held over 88% of the market. I extend the network demand system of Björkegren (2019) to allow for competition, and add a tractable supply side to compute full equilibria between firms and 1.5 million networked consumers. I evaluate how introducing competition earlier would affect prices, investment, and welfare. This paper represents the first empirical analysis of competing classical network goods using micro data.\footnote{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.}

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, which has two useful features. The competitor who entered ended up being mismanaged in a ‘quixotic’ fashion (WSJ 2006) and as a result never captured much market share. While facing this competitor, the incumbent lowered real calling prices by 76% and nearly quadrupled the number of towers, increasing coverage from 60% to a nearly complete 95% of land area. Because of these two features, I observe nearly the entire network of mobile phones in Rwanda under substantial variation in price and coverage.

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. If this additional competitor had been granted a license
earlier and split the network, what would have happened? Would the incumbent still have built coverage in rural areas?

I answer these questions using an empirical approach that has four parts. Because outcomes in a network industry depend on the network structure of demand, the model of demand is central.

First, 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. 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 by the second, so a subscriber must value a connection at least as much as the cost of calls placed across it. Variation in prices and coverage identifies the underlying demand curve for communication across each link, for nearly the entire mobile phone network at the time.

Second, 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. 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 commit to 5 year tower rollout plans. I also require firms to commit to a path of calling prices, allowed to be proportional to the observed monopoly price path. 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 build either the nearly complete set of towers built under monopoly, or to build only in cities and the highest population density areas.

Even as of this writing, only 9% of mobile phones in Rwanda are smartphones (ResearchICTAfrica, 2017). In the first 14 months of the data, calls are billed by the first minute and every following 30 seconds.
rural areas. To limit the multiplicity of equilibria, I require that firms charge the same rate for on- and off-network calls. Because these are feasible terms of competition, my results represent a lower bound of the potential welfare benefits of competition. 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. Firms select prices and rollout plans; then, consumers publicly announce adoption dates and operator choices. I exploit supermodularity in adoption and operator choices to index the multiple equilibria in demand (similar to Jia (2008) and Björkegren (2019)), and assume that firms anticipate the index of the equilibrium that consumers will play.

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 through December 2008. I hold fixed the network and behavior of the poorly performing entrant.

At baseline the incumbent’s mobile phone system was an important part of Rwanda’s economy, providing net social welfare of $334-386m, an amount equivalent to 2-3% of GDP over the same period.

Under all interconnection policies I assess, the incumbent would find it profitable to build rural towers. Under competition, the return on investment (ROI) can be higher than monopoly, but declines as the networks are made more compatible.

There is a focal competition policy (setting the interconnection rate to $0.11/minute) where competition would have lowered prices by 30-50% and increased incentives to invest in rural towers\(^\text{11}\). Competition affects incentives to invest through three forces. First, lowered prices reduce the total revenue generated by 39-41%. Second, when the

\(^{11}\)This rate is 25% higher than the rate the government had set at the time.
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. Under the focal policy, the business stealing effect dominates foregone network effects: it accounts for 64-70% of the revenue the incumbent earns from building the rural network. The business stealing effect is large because there are many semiurban consumers who trade off prices and rural coverage.

Licensing a competitor earlier under these terms would have increased the net welfare provided by the mobile phone system by up to 60%, an amount equivalent to 1% of GDP or 3-5% of the official development aid received by the country over this 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, the incumbent would have effectively blocked access to its network. This outcome is similar to previously unregulated Somalia, where it was not possible to call between competing mobile phone networks, and is reminiscent of many network industries that do not endogenously develop compatibility (Katz and Shapiro, 1985).

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

In order to correctly measure network effects, my model accounts for the full structure of the network. An isolated node will tend to have less spillover effects than a central node, independent of the intensity of its links. In contrast, in nonnetwork demand systems it is common to treat individual consumer decisions as independent, or to aggregate demand. I show that such models misestimate the revenue from investment by 52-86% because they mischaracterize network effects. I combine a sophisticated network demand system that correctly accounts for these effects with a

\[\text{These results are similar in flavor to Goettler and Gordon (2011), which finds that the effect of competition on investments in innovation can vary based on industry primitives.}\]
simple supply side to analyze a new tradeoff: how investment is affected by splitting a network. Because I observe the industry over a long horizon (4.5 years), my results also capture some intertemporal tradeoffs, but those are not my focus. My model is consistent with firms renting towers over a specified time horizon, and my qualitative results are not sensitive to firms’ time horizons.

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 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 $G$, with links $ij \in G$. Each consumer $i \in G$ takes an action $x_i^a(x_{-i}, p, \phi_i^a)$ on each firm’s network $a \in A$. The action depends on the actions of others $x_{-i}$, the price $p$, and a nonnetwork dimension of quality $\phi_i^a$, which may be differentially useful to different individuals (for example, cellular coverage or a particular feature).

Incentives to invest in quality differ by market structure:

**Monopoly.** The firm’s profits depend on consumers’ actions:

$$\pi(p, \phi) = \sum_{i \in G} p \cdot Q(x_i(x_{-i}, p, \phi_i)) - c(\phi)$$

where $p \cdot Q(\cdot)$ is the revenue associated with an action, and and $c(\phi)$ is the cost of investment (where some quality may be joint between some individuals).

Increasing the quality available to $i$ ($\phi_i$) directly influences $i$’s action (a proximal effect). But when demand is networked, changing $i$’s action also induces a change in the equilibrium actions of others. In shorthand,
\[
\frac{d\pi}{d\phi_i} = p \cdot \frac{\partial Q_i}{\partial x_i} \left[ \text{Proximal effect} + \sum_{k \in G} \left[ \sum_{\text{all paths } i \rightarrow k \in G} \frac{\partial x_{j_1}}{\partial x_i} \cdots \frac{\partial x_k}{\partial x_{j_N}} \right] \frac{\partial Q_k}{\partial x_k} \right] - \frac{\partial c}{\partial \phi_i}
\]

where ripple effects are induced through all paths in the network. In the same setting as this paper, [Björkegren (2019)](Björkegren2019) 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.** Larger networks internalize more ripple effects, and so have larger incentives to invest in quality, even in absence of scale economies in cost. Splitting a network with 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. Third, firms may invest to induce marginal consumers to switch networks (a business stealing effect).

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 the structure of the network interacts with preferences for, and costs of providing, quality.

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](ITU2011)). As component costs decreased, handsets became accessible even 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.)

---

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.
As these networks grew, regulators licensed multiple operators to compete in providing service (see Figure 1), recognizing that monopoly networks may not be sufficiently disciplined. 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, but attached to the license was a requirement that the operator build out rural coverage in a small number of priority areas (amounting to 11% of rural towers active by 2009; Björkegren (2019)).

These included border crossings, major roads, and district centers.
Figure 1. Mobile Telecom Competition in sub-Saharan Africa


Table 1. Mobile Telecommunications in sub-Saharan Africa

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of operators</td>
<td>3.27</td>
<td>1.48</td>
</tr>
<tr>
<td>...top market share</td>
<td>0.58</td>
<td>0.19</td>
</tr>
<tr>
<td>...second highest market share</td>
<td>0.32</td>
<td>0.09</td>
</tr>
<tr>
<td>Market concentration (HHI)</td>
<td>0.49</td>
<td>0.21</td>
</tr>
<tr>
<td>Interconnection charges are regulated</td>
<td>97%</td>
<td></td>
</tr>
<tr>
<td>...based on costs (LRIC or FDC)</td>
<td>71%</td>
<td></td>
</tr>
<tr>
<td>...based on benchmarks</td>
<td>43%</td>
<td></td>
</tr>
<tr>
<td>...asymmetrically between operators</td>
<td>31%</td>
<td></td>
</tr>
</tbody>
</table>

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.

In 2003, the government announced it would provide a license to a second mobile operator, which entered the market in 2005 (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 as ‘quixotic’ (WSJ, 2006). 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. Because the incumbent already expected a firm to enter in 2005 and did not know its type, the starting conditions include any dynamic effects of anticipating future entry.

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. In response to 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. 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. My model will capture the key differentiators (coverage and pricing).

In Rwanda, almost all phone plans are prepaid, with no monthly fee but a marginal charge by second of talk time. Handsets are standard, imported models, with prices

---

15WSJ (2006) reports that the operator ‘had no customer-service department and 12 employees whose sole job was to play on the company soccer team.’ The Registrar General, Louise Kanyonga said, “The company was mismanaged and their liabilities far outweigh their assets... This has been a real learning experience for our government. We need to ask how this happened.”

16Operator 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.

17See Supplemental Appendix: Operator Differentiators for more details.
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 $0.11 per minute. Sources: archived operator websites and regulator reports.
Table 2. Mobile Phone Usage among Owners in sub-Saharan Africa

<table>
<thead>
<tr>
<th>Received phone with a contract</th>
<th>2007-8</th>
<th>2010-11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rwanda</td>
<td>SSA**</td>
<td>Rwanda</td>
</tr>
<tr>
<td>0%</td>
<td>3%</td>
<td>3%</td>
</tr>
</tbody>
</table>

**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.

that track global trends. Most are purchased from independent sellers.\(^{18}\) 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.\(^{19}\) Any value these omissions provide will be captured in a residual when I estimate the adoption decision.

---

\(^{18}\) Operator handset sales records account for only 10% of total handsets activated during the period of my data.

\(^{19}\) 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.\(^\text{20}\)

**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, timestamps, the location of the cell towers used, and call duration.\(^\text{21}\) 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, \(z = \{(t_z, x_z, y_z)\}_z\), is defined by tower build dates and geographical coordinates. I consider the baseline rollout, \(z(100\%)\), 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

---

\(^{20}\)For more information see Supplemental Appendix.

\(^{21}\)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 $\phi_t(x, y; z)$ represents an average of the coverage available near $(x, y)$ under rollout plan $z$, 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, $d_{il}$: $\phi_{il}(z) = \frac{\sum_l \phi_t(x_{il}, y_{il}; z) \cdot d_{il}}{\sum_l d_{il}}$.

**Handset prices:** I create a monthly handset price index $p^{\text{handset}}_t$ 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 arrives in $t = 0$ with an initial set of subscribers and towers. The government announces a policy environment (competitor entry date, and interconnection terms $f$), and the game proceeds in three steps. First, the entrant selects a path of prices $p^1$, and commits to build towers in urban areas. Second, the incumbent selects a path of prices $p^0$ and a tower rollout plan $z^0$. Third, each consumer decides when to adopt a phone ($x_i$), and each period 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. For ease of exposition I refer to accounts as individuals or nodes.\(^{22}\)

\(^{22}\)I assume that each account is associated with a unitary entity such as an individual, firm, or household. If the composition of people using a handset changed over time (say, if a couple initially shares...
I observe the communication graph $G^0_T$, where a directed link $ij \in G^0_T$ indicates that $i$ has called $j$ by period $T$ while both subscribed to the incumbent. Define $G_i = \{j | ij \in G^0_T\}$ as $i$’s set of contacts, and $S_t \subseteq N$ as the set of individuals with phones in month $t$. The graph I observe omits any ‘dark’ nodes $i \in N \setminus S_T$ 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. The network I observe omits the small number of subscribers of the incumbent’s first competitor; I assume that these individuals’ usage remains the same in any counterfactual, so my results will tend to underestimate the effects of competition.

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:

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

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

---

23 $G^0_T$ is a subgraph of $\bar{G}$ the full communication graph of Rwanda (a directed social network), with $N$ nodes representing all individuals in the country. A directed link $ij \in \bar{G}$ indicates that $i$ would have a potential desire to call $j$ via phone. I assume that links are fixed. Let $S_t \subseteq N$ be the set of individuals with phones in month $t$. I observe only individuals who adopt the incumbent by the end of my data $T$, the set $S^T_0 \subseteq N$. This will miss any links between subscribers where there is a latent desire to communicate but no call has been placed by $T$ ($G^0_T \subseteq G^0_T$). See Supplemental Appendix.
I model the benefit of making calls as:

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

for \( \epsilon > 0 \), where the first term is a linear benefit; \( \gamma > 1 \) controls how quickly marginal returns decline, and \( \alpha \geq 0 \) controls how the intercept of marginal utility varies with the shock, and thus the fraction of months for which no call is placed.\(^{24}\)

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

\[ c_{ijt} = p_{it}^{a_{it}a_{jt}} + \beta_{\text{coverage}} \phi_{it}^{a_{it}} \phi_{jt}^{a_{jt}} \]

where \( p_{it}^{a_{it}a_{jt}} \) 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 (\( p_{it}^{a_{it}a_{jt}} = p_{it}^{a_{it}} \)). Each firm offers its own coverage; if \( i \) subscribes to firm \( a \) in month, he will receive coverage \( \phi_{it}^{a_{it}} \in [0, 1] \), based on the fraction of the area surrounding his most used locations within line of sight of the firm’s towers. \( \beta_{\text{coverage}} \phi_{it}^{a_{it}} \phi_{jt}^{a_{jt}} \) 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:

\[ d(\epsilon, \mathbf{p}_t, \phi_t, \mathbf{a}) = \left[ \epsilon \left( 1 - \beta_{\text{cost}} (p_{it}^{a_{it}a_{jt}} - \beta_{\text{coverage}} \phi_{it}^{a_{it}} \phi_{jt}^{a_{jt}}) \right) \right]^{\frac{1}{\gamma - 1}} - \alpha \]

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

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

\[ E \! d_{ij}(\mathbf{p}_t, \phi_t, \mathbf{a}) = \int_{\epsilon_{ijt}}^{\infty} d(\epsilon, \mathbf{p}_t, \phi_t, \mathbf{a}) \cdot dF_{ij}(\epsilon) \]

\(^{24}\)This functional form was chosen to satisfy 8 reasonable properties for the utility from telephone calls; see Björkegren (2019).
and provide expected utility:

\[
Eu_{ij}(p_t, \phi_t, a) = \int_{\mathbb{R}_{ij}} \left[ d(\epsilon, p_t, \phi_t, a) \cdot \left( \frac{1}{\beta_{\text{cost}}} (1 - \frac{\alpha}{\epsilon}) - p_t^{a_{it}} - \beta_{\text{coverage}} \phi_t^{a_{it}} \right) - \frac{1}{\beta_{\text{cost}}} \frac{d(\epsilon, p_t, \phi_t, a)^\gamma}{\gamma} \right] dF_{ij}(\epsilon)
\]

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

\[
Eu_{it}(p_t, \phi_t, a, x_{G_i}) = \sum_{j \in G_i \text{ and } x_j \leq t} Eu_{ij}(p_t, \phi_t, a) - s \cdot 1_{\{a_{it} \neq a_{it-1}\}}
\]

where \(x_j\) represents \(j\)'s adoption time and \(s\) represents the cost of switching operators.\(^{25}\) However, at the point of adoption, \(i\) anticipates that having a phone in month \(t\) will provide utility:

\[
E\hat{u}_{it}(p_t, \phi_t, a, x_{G_i}) = Eu_{it}(p_t, \phi_t, a, x_{G_i}) + \eta_{i}^0(1 - \delta)
\]

where an individual’s type \((\eta_{i}^0, \eta_{i}^1)\) 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.

**Adoption decision.** Conditional on the decisions of others, an individual’s adoption decision is an optimal stopping problem. At period \(t\), \(i\) knows the current price of a handset, \(p_t^{\text{handset}}\) (inclusive of any tax), and knows that his contacts will adopt at times \(x_{G_i}\). He has a deterministic belief that in period \(x > t\), the handset price will be \(E_t p_x^{\text{handset}}\).

The adoption decision proceeds in two steps:

First, consumer \(i\) decides when to purchase a handset, under deterministic belief that each contact \(j\) will use the operator \(\hat{a}_j\) that is optimal given coverage in their

\(^{25}\)This would include the cost of changing accounts (swapping SIM cards and adjusting any settings), and notifying contacts about the change in phone number. Björk gren (2019) also considers the possibility that consumers receive value from incoming calls, but finds that this double counts the utility from calls.
location (in a sense defined later). He expects that adopting at time $x$ with operator sequence $a_i$ will yield utility:

$$U_x^{a_i}(\mathbf{p}, \phi, \mathbf{x}_{G_i}, \hat{a}_{G_i}) = \delta^x \left[ \sum_{s \geq x} \delta^{s-x} E\hat{u}_{i,s}(\mathbf{p}_s, \phi_s, [a_i, \hat{a}_{G_i}], \mathbf{x}_{G_i}) - E_t p_{handset} \right]$$

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

$$\min x_i \text{s.t.} \left[ \max_{a_i} E_{x_i} U_x^{a_i}(\mathbf{p}, \phi, \mathbf{x}_{G_i}, \hat{a}_{G_i}) \geq \max_{s \geq x_i, \hat{a}_i} E_{x_i} U_x^{\hat{a}_i,s}(\mathbf{p}, \phi, \mathbf{x}_{G_i}, \hat{a}_{G_i}) \right]$$

Second, upon purchasing a handset, consumer $i$ learns his contacts’ operator choices (updating $\tilde{a}_j = a_j$), and selects operator sequence $a_i$ to maximize utility (Equation 5).

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 $\bar{T} \leq T$.

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

$$U_{net}^{\bar{T}} = \sum_{i \in S_T} \left[ \sum_{x \leq \bar{T}} \delta^x E u_{i,t}(\mathbf{p}_t, \phi_t, a, \mathbf{x}_{G_i}) - \left( \delta^x p_{handset} - \delta^{\bar{T}} p_{handset} \right) \right]$$

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

$$\pi_{\mathbf{F}}^{\bar{T}}(\mathbf{p}, \mathbf{z}, \mathbf{a}, \mathbf{x}, \mathbf{f}) = R_{\mathbf{F}}^{\bar{T}}(\mathbf{p}, \mathbf{z}, \mathbf{a}, \mathbf{x}, \mathbf{f}) - C_{\mathbf{F}}^{\bar{T}}(\mathbf{p}, \mathbf{z}, \mathbf{a}, \mathbf{x})$$

These are enforced: when Operator B failed to comply with its rollout plan, it was fined and its license was ultimately revoked.
Figure 3. Rollout Plans

Incumbent Plan $z^0 \in$

- $z_{(100\%)}$
  All towers

- $z_{(50\%)}$
  Do not build half of rural towers covering lowest population

Entrant Plan $z^1 =$

- $z_{(0\%)}$
  Only urban towers

Coverage shaded; points denote cities. National parks shaded in light green; Lake Kivu shaded in light blue.

where $p = [p^0, p^1]$ and $z = [z^0, z^1]$. Firms may select calling prices from a multiple of the monopolist price path: $p^F \in \psi \cdot p^{monopoly}$, given grid $\psi \in \{0.1 \cdot n|n \in 1...10\}$.

It tends to be more lucrative to build towers in more populous areas: they cover more people and operating costs tend to be lower. For urban towers, I assume firms build the same 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, starting from the monopoly rollout which included nearly all desirable tower locations in the country. I assume that the entrant follows its parent company’s articulated strategy in Africa (and later initial plan in Rwanda) and builds only urban
towers: \( z^1 = z(0\%) \). I allow the incumbent to build out nearly complete coverage as in the monopoly baseline, or only the 50% of rural towers covering the highest populations: \( z^0 \in \{ z(100\%), z(50\%) \} \) (see Figure 3).27

Firm \( F \) earns revenue from the calls of its own subscribers and from interconnection fees charged to the competitor’s subscribers who call in to the network:

\[
R^F_T(p, z, a, x, f) = \sum_{i \in S_T} \sum_{t \geq x_i} \sum_{j \in G \cap S_t} \delta^t \sum_{x_t} \text{Ed}_{ij}(p_t, \phi_t(z), a) \cdot \left[ \frac{1}{(1 - \tau_{usage}^{t})} \frac{g_{a_i a_j} \cdot 1 \{ a_i = F \} + f_{ij} \left[ 1 \{ a_i \neq F \} \cap \{ a_j = F \} \right] - 1 \{ a_i = F \} \cap \{ a_j \neq F \} \right] \]
\]

where \( \phi_t(z) \) is the coverage provided at time \( t \) under the rollout plans \( z = \{ z^0, z^1 \} \), \( \tau_{usage}^{t} \) represents the airtime tax rate, and \( f_{ij} \) is the interconnection rate.

Firm \( F \) incurs costs:

\[
C^T_F(p, z, a, x) = K_{rural} \cdot \sum_{z \in z^F, z \text{ is off grid}} \sum_{t \geq x^\text{lower}_t} \delta^t + \sum_{t \geq \min\{ x^\text{lower}_t \} } \delta^t f_{cF} +
\]

\[
+ \sum_{i \in S_T} \sum_{t \geq x_i} \sum_{j \in G \cap S_t} \delta^t \sum_{x_t} \text{Ed}_{ij}(p_t, \phi_t(z), a) \cdot \left( i_{c_{L_i, \text{onnet}_{ij}}}^{out} \cdot 1 \{ a_i = F \} + i_{c_{L_j, \text{onnet}_{ij}}}^{in} \right)
\]

Firms act as though they rent towers: \( K_{rural} \) represents the annualized cost of owning and operating a rural tower.28 Each month that its network is operational, operator \( F \) also incurs fixed cost \( f_{cF} \). \( i_{c_{L_i, \text{onnet}_{ij}}}^{direction} \) 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 (\( L_i \in \{ \text{urban, rural} \} \)).

---

27In Rwanda during this period, mean monthly revenue from an urban tower is nearly twice that of a rural tower. In the Supplemental Appendix, I separately find that the towers built under the government coverage obligation that were not profitable under monopoly are profitable under competition.

28A tower is considered urban if it covers Kigali or one of Rwanda’s 5 largest towns; a subscriber is considered urban if his most used tower is urban.
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:

$$R_G^T(p, z, a, x) = \sum_{i \in S_T \text{ and } x_i \leq \bar{T}} \left[ \delta^{x_i \text{handset}}_{z_i} p_{z_i} \text{handset} + \sum_{t \geq x_i} \left( \delta^{x_i \text{usage}} \sum_{j \in G_i \cap S_t} p_{t}^{a_{i \text{med}}, j} \cdot E_{ij}(p_t, \phi_t, a) \right) \right]$$

This includes revenue from taxes on adoption ($\tau_{it}^{\text{handset}}$) and usage ($\tau_{it}^{\text{usage}}$), which I hold fixed.\(^{29}\) 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, given consumer types $\eta$, interconnection terms $f$, and horizon $\bar{T}$, a **subgame perfect equilibrium** of index $e$ is $(p^0, p^1, z^0, z^1, a, x, d)$ such that:

1. **The entrant** selects price sequence $p^1$, and constructs urban towers $z^1 = z_{(0\%)}$
2. **The incumbent** selects price sequence $p^0$ and tower construction plan $z^0$
3. **Consumers** adopt at times $x = x(p, z, \eta, e)$, using operators $a = a(p, z, \eta, e)$ and placing calls $d$ such that:

   - Each initial adopter $i \in S_0$ selects operator sequence $a_i \in \{0, 1\}^\bar{T}$ optimally, believing each contact $j$ will adopt at time $x_j$ using operators $a_j$
   - Every other observed adopter $i \in S_T \setminus S_0$ selects:
     - adoption date $x_i \in \{1, \ldots, \bar{T}\}$ optimally, believing each contact $j$ will adopt at time $x_j$ using operators $\tilde{a}_j(p, \phi_j, \phi_{\text{median}})$
     - operator sequence $a_i \in \{0, 1\}^{\bar{T} - x_i}$ optimally, believing each contact $j$ will adopt at time $x_j$ using operators $a_j$
   - After adoption, $i \in S_T$ calls each contact $j \in G_i \cap S_t$ for $d_{ijt} = E_{ij}(p_t, \phi_t, a)$ seconds in month $t$

\(^{29}\)At the time, Rwanda taxed handsets at 48% and usage at 23%.
5.5. **Expectations.**

**Firms.** Under a structural approach, equilibria are computed under specified expectations about the future. In my model, firms maximize net present profits through horizon $\tilde{T}$, which implies that they neglect the value of their accumulated stock of subscribers after $\tilde{T}$. Because firms neglect this continuation value, my results will underestimate incentives to invest in a competitive environment. That does not have a major impact on results because firms do not control handset prices, which is a major determinant of adoption.\(^{30}\) Tower investments do affect adoption, but I only allow firms to select among rollout plans that would make reasonable long term investments. My baseline results report $\tilde{T}$ for a long period (4 years), and in the Supplemental Appendix I find that results do not differ substantially under different choices of $\tilde{T}$, including the full period of data plus the final period repeated for three years (representing a total horizon of 7.5 years).

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 $(p^0, p^1, z^0, z^1)$, firms believe that in the subgame resulting from actions $(p'^0, p'^1, z'^0, z'^1)$, 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 $e^A$ 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 ($e$) 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

\(^{30}\)Cellular contracts and adoption subsidies are extremely rare in sub-Saharan Africa; handset prices are driven by global trends (see Table 2).
because adoption equilibria form a lattice: \( i \)'s optimal adoption date \( x_i \) is weakly monotonic in his type \( \eta_i \), contact's adoption date \( x_j \), and contact's coverage \( \phi_{aj} \). \(^{31}\)

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.\(^{32}\)

**Consumers.** Within equilibrium \( e \), individuals correctly forecast call prices \( p_x \), coverage \( \phi_x \), and their contacts' adoption dates \( x_{G_i} \).

Because a handset becomes sunk at the time of purchase, forecasts of future prices can sway the adoption decision.\(^{33}\) 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:

\[
E_t p_{x, \text{handset}} = \omega^{x - t} p_t^{\text{handset}}
\]

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

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 \( T \).\(^{34}\) This avoids nonmonotonicities in adoption equilibria.

\(^{31}\)A higher type \( \eta_i \) weakly decreases \( i \)'s optimal adoption date, and a decrease in \( i \)'s adoption date \( x_i \) or coverage \( \phi_i \) weakly decreases \( j \)'s optimal adoption date. This follows from the lattice structure of \( x \) and because \( U^x(\eta_i, x_i, \phi_{aj}) \) has increasing differences in \( x_i \) and \( x_j \), or is supermodular in \( x \); see Topkis (1978) and Milgrom and Shannon (1994).

\(^{32}\)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 \( p^F \equiv \bar{p} \), consumers will adopt according to the fastest adoption equilibrium, but for \( p^F \neq \bar{p} \), 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 \( p^F \equiv \bar{p} \), the equilibrium will favor \( F \), but for \( p^F \neq \bar{p} \) the equilibrium will favor \(-F\).

\(^{33}\)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.

\(^{34}\)That is, \( \hat{a}_j(p, \phi) = \arg \min_a \left[ p_{T}^{aa} + \beta \text{coverage} \phi_{aj} \phi_{amT} \right] \), for median individual \( m \), who selects his operator analogously: \( a_m = \hat{a}_m(p, \phi_m) \). 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.
Once $i$ has purchased a handset, he selects an operator anticipating contacts’ actual operator choices ($\hat{a}_j = a_j$).

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. If at the point of adoption, an individual forecasts differently than specified here, the error will be captured in his type $(\eta^0_i, \eta^1_i)$, 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.

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

Firms’ action spaces rule 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. 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.

They also rule out the possibility that either firm would build towers in locations that were not served under monopoly. These are few—as shown in Figure 3, the

---

35It implies that individuals do not anticipate how later adopters will respond to their actions, because later adopters may not condition their strategy on actions in prior periods. It also introduces a slight inconsistency: when $i$ decides whether to adopt in period $x_i$, he does not know future handset prices, but does know the adoption dates of his future contacts, which will have incorporated future handset prices. I tolerate this inconsistency in order to have a computable notion of equilibrium.

36To 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.
monopoly’s rollout plan \((z_{(100\%)}\) was nearly complete. If competition induces firms to build towers in new locations, my results will represent a lower bound on the effects of competition on investment.

6. Estimation

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

**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 (\(\gamma\) and \(\alpha\)), and how usage responds to cost (\(\beta_{\text{cost}}\) and \(\beta_{\text{coverage}}\)). The adoption decision reveals any residual factors affecting adoption of the incumbent (bounds on individual types \([\eta_{0i}, \eta_{1i}]\)). 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.

Holding fixed prices and coverage, consumers have a slight idiosyncratic preference for the incumbent, with a difference with mean \(m(\eta_{0i} - \eta_{1i}) = 2.45\ ($0.01 per month), and standard deviation \(\sigma(\eta_{1i} - \eta_{0i}) = 6.72\). These preferences are not correlated with observables, and when asked to explain their choices, the most common response was a preference for one operator’s branding or color scheme. In counterfactual simulations,
I treat these differential preferences as random parameters: for each individual I draw $e_i \sim iid N [m(\eta^0_i - \eta^1_i), \sigma(\eta^1_i - \eta^0_i)]$, and compute his type under the entrant $[\bar{\eta}^1_i, \bar{\eta}^0_i] = [\eta^0_i - e_i, \eta^0_i - e_i]$. 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 which can be observed in the data. It is much less costly to switch between plans on the same operator; actions in the data are consistent with an intra-operator switching cost of $6.83. I find that this does not differ significantly at the 1% level from the estimate formed from analogous hypothetical choices.\(^{37}\)

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 $f_c F$ and the incremental costs of scaling the size of the network $i c^L_{onnet_{ij}}$ 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.\(^{38}\) 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%).

\(^{37}\)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.

\(^{38}\)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.\footnote{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).} 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 ($L_i = \text{urban}$), I include the cost of towers in incremental costs. For subscribers who primarily use rural towers ($L_i = \text{rural}$), I compute the cost of towers separately.

I infer the annualized cost of building and operating a rural tower, $K_{\text{rural}}$, from \textit{RURA} (2011), a public study commissioned to set the regulated prices of infrastructure sharing based on cost data from operators.\footnote{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.}

Validation. Because Rwanda’s regulator does not intervene in consumer telecom prices, the monopolist’s price choices allow a consistency check. Under these cost estimates, the monopolist’s chosen prices are profit maximizing (see Supplemental Appendix). Although the cost estimates behind most interconnection studies are confidential, the interconnection rates recommended by \textit{PwC} (2011) based on those costs are similar ($0.07$ per minute) to those recommended on average in Africa ($0.08$ per minute; \textit{Lazauskaite} (2009)), suggesting costs are similar to other African markets.
7. SIMULATION

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

- Operators cannot charge different prices for on- and off-net calls ($p_{t}^{F,G} = p_{t}^{F,G'}$)
- 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. Given policy choices $f$, equilibrium index $e \in \{e^{A}, \bar{e}^{A}\}$, and individual types $\eta$, I identify a subgame perfect equilibrium by in three nested steps:

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

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

3. **Consumer choices**
   Conditional on $p$ and $z$, I use an iterated best response method:

   - **Adoption dates $x$**: I initialize with a candidate adoption path representing a complete delay of adoption for $e^{A}$ ($x^{0} = \bar{T}$), or immediate adoption for $\bar{e}^{A}$ ($x^{0} = 0$). I sequentially allow each individual to optimize their adoption date $x_{i}$, conditional on the adoption dates of others $x_{-i}$ and with beliefs about others’ operators $\hat{a}_{-i}(p, \phi_{-i}, \phi_{median})$, until $x$ converges.

   - **Operators $a$**: Conditional on equilibrium adoption dates $x$, I initialize with candidate operator choices $a^{0} \equiv A$: all individuals subscribe to operator $A$. I sequentially allow each individual $i$ to optimize their operator choice $a_{i}$, conditional on the actual operators their contacts will use ($\hat{a}_{-i} = a_{-i}$), until $a$ converges.
For the lower equilibrium $e^A$, I set individuals’ types to their lower bound ($\eta = \underline{\eta}$), 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 ($\eta = \bar{\eta}$), and thus will recover an upper bound of the adoption equilibrium.\footnote{See Supplemental Appendix for the implementation of the algorithm.}

**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 \footnote{Including Kenya, Singapore, Colombia, Turkey, Slovenia, and Portugal; see TMG (2011).} \cite{ArgentPogorelsky2011}, and has been used in several countries in an attempt to discipline competition.

In markets where different operators have low on-net prices and high off-net prices, consumers may hold accounts with multiple operators to connect with contacts on different networks. Given that 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 \cite{RIA2012} 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).
Computing a single partial equilibrium takes about 15 hours on a high performance computing node, so that computing the over 1,800 partial equilibria used in this paper takes over 1,125 computer days.

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

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

**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.

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

---

43To 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.

44This represents a lower bound because results through \( T \) do not include benefits to the dark network.
Table 3. Benchmark Monopoly Simulations (million $, 2005-5.2009)

<table>
<thead>
<tr>
<th>Impact:</th>
<th>Consumer Surplus</th>
<th>Gov. Revenue</th>
<th>Firm Profits</th>
<th>Firm Revenue Breakdown</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All links</td>
<td>All links</td>
<td>All links</td>
<td>All links</td>
</tr>
<tr>
<td>Baseline</td>
<td>[244, 270]</td>
<td>[65, 73]</td>
<td>[122, 140]</td>
<td>[30, 33]</td>
</tr>
<tr>
<td>Charge eventual</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>competitive price</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>... only proximal effect</td>
<td>+330, +338</td>
<td>-2, -4</td>
<td>-51, -62</td>
<td>-4, -5</td>
</tr>
<tr>
<td>... additional ripple effects</td>
<td>+288, +316</td>
<td>-7, -9</td>
<td>-58, -67</td>
<td>-5, -6</td>
</tr>
<tr>
<td>No rural expansion</td>
<td>-81, -92</td>
<td>-11, -14</td>
<td>-19, -27</td>
<td>-9, -10</td>
</tr>
<tr>
<td>... only proximal effect</td>
<td>-77, -83</td>
<td>-10, -11</td>
<td>-17, -21</td>
<td>-8, -9</td>
</tr>
<tr>
<td>... additional ripple effects</td>
<td>-3, -8</td>
<td>-1, -2</td>
<td>-2, -6</td>
<td>-0, -1</td>
</tr>
<tr>
<td>Charge eventual</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>competitive price &amp; no</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rural expansion</td>
<td>+198, +217</td>
<td>-10, -11</td>
<td>-56, -66</td>
<td>-10, -10</td>
</tr>
<tr>
<td>... only proximal effect</td>
<td>+155, +200</td>
<td>-14, -14</td>
<td>-62, -69</td>
<td>-10, -11</td>
</tr>
<tr>
<td>... additional ripple effects</td>
<td>+43, +17</td>
<td>+4, +3</td>
<td>+7, +3</td>
<td>+1, +1</td>
</tr>
</tbody>
</table>

any additional network effects as the impact of these decisions ripple through the network (row 4). Network ripple effects account for 24% (21%) of the revenue change and 19% (11%) of the welfare increase. Because an aggregate demand function would not account for these effects, it would misstate the effect of changing prices.

**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 ($z^0 = z_{(100\%)}$) relative to a counterfactual where only urban towers are built ($z^0 = z_{(0\%)}$; 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 row 5, most of the revenue from building rural towers does not come from rural calls: rural-rural links generated only 28% (24%) of the additional revenue. 31% (29%) came from links between rural and urban areas. 44% (48%) of the revenue from building rural towers came from increased calling on urban-urban links:

- 92% (75%) of urban-urban revenue comes from proximal effects (row 6): some urban consumers make calls from rural areas and thus directly benefit from rural coverage (which would be included in their coverage measure $\phi_{it}^a$). These consumers create incentives to compete on the quality of rural coverage.
- 8% (25%) of urban-urban revenue comes from network spillover effects (row 7), 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 Table 3 rows 8-10.

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

9. RESULTS UNDER COMPETITION

I next allow the entrant to offer service starting in January 2005, and simulate equilibria where the entrant selects prices, the incumbent selects prices and a rollout plan, and consumers adjust adoption dates and operator choices in a network adoption equilibrium. I present 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
Figure 4. Equilibrium Results as Function of Interconnection Rate

|                  | Baseline | Counterfactual
|------------------|----------|-----------------|
|                  |          | Holding Rollout Plans Fixed
| Monopoly         |          | Additional Competitor

- C Surplus
- Gov Revenue
- Profit Entrant
- Profit Incumbent
- high
- low

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.

but are required to interconnect subscribers. Given that the incumbent was naturally focal, the main text reports incumbent favoring equilibria.
I find that competition has the potential to dramatically improve welfare, and for some policies can increase incentives to invest in rural towers. Specifically, I find:

9.1. **Increasing compatibility lowers prices and incentives to invest.** Figure 4 shows equilibrium outcomes as a function of the interconnection rate, which is a measure of compatibility (shown decreasing with the x-axis). As the interconnection rate is lowered, price competition becomes more intense (top panel), and welfare increases and incumbent profits decline (middle panel). Across all interconnection rates, in equilibrium the incumbent would elect to build the rural towers covering the lowest 50% population density locations. The return on the investment starts above the monopoly, and tends to decline as the interconnection rate is lowered (bottom panel). (Outcomes also shown in Table A3.)

9.2. **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 ($f_{ij} = 0.33$). The incumbent and entrant both charge 80% (90%) of the monopoly price, and consumer surplus is only somewhat higher that the monopoly case (shown in Table A3 row 2). 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

---

45Results 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.

46I allow the incumbent to select the interconnection rate on a grid from $0.00 to $0.43.

47The 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.
of theoretical results that suggest that if firms select the interconnection rate, they may use it as an instrument of collusion to sustain high prices (Armstrong 1998; Laffont et al. 1998).

9.3. **Competition can lower prices and increase incentives to invest.** The government can select an interconnection rate that lowers prices, increases incentives to invest, and dramatically improves welfare. A focal rate 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. 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.\(^{48}\) (Outcomes are also shown in the third row of Table A3.\(^{49}\))

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).\(^{50}\) 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

\(^{48}\)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.

\(^{49}\)The price series is shown in Figure 2 and the resulting normal form games are shown in Tables A1 and A2.

\(^{50}\)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.
entrant, which offers poor rural coverage. (For more on diversion ratios see Conlon and Mortimer (2018).)

This focal interconnection rate is slightly higher than the level the regulator used at that time ($f_{ij} = $0.09), or was recommended based on the consultant report ($f_{ij} = $0.07, (PwC 2011)). It is also higher than the zero rated interconnection rate ($f_{ij} = $0: ‘bill and keep’, to which the U.S. is transitioning (FCC 2011)). As shown in both Figures 4 (and Table A3 row 7), these lower interconnection rates would result in lower prices and higher welfare. The incumbent would still have found it profitable to build rural towers, but it would earn a lower return than under monopoly.

Incentives to invest are driven by business stealing. To better understand the investment effects, I start from an adoption equilibria where tower investments are removed, and then consider how the market would respond when these investments are added back, culminating in the full equilibrium. I first consider the focal interconnection rate ($f_{ij} = $0.11). Table 4 decomposes three effects:

1. Competition lowers overall revenues. Under monopoly, building these towers generated total revenue of $2.57m ($2.46m). Under competition, prices are lower, and the investment generated net revenue of $1.52m ($1.51m) combined between the two operators. This is shown in Table 4 rows 1-2.

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.

When the incumbent faces a competing network, some of the revenue accrues to the entrant, due to network effects. In this case, foregone network effects are relatively small. When the incumbent adds the investment but operator choices are held fixed, the incumbent captures 93% (88%) of the revenue, as shown in Table 4 row 3. The remaining 7% (12%) of revenue accrues to the entrant.51

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 paid back through interconnection. However, 1% (0.2%) of the revenue results from spillovers in the interior of the entrant’s network (entrant on-net calls). Since interconnection fees are incurred
On net, these two effects 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. Table 4 row 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.

Discussion. The Supplemental Appendix presents partial equilibrium results for an expanded set of rollout plans \((z^0 \in \{z_{(100%)}, z_{(75%)}, z_{(50%)}, z_{(25%)}, z_{(0%)}\}\) versus \(z^1 = z_{(0%)})\), holding fixed prices. For all plans, the ROI of building low population towers is weakly larger under the focal competition policy. I also find that the 10 towers built under government coverage obligation that are unprofitable under monopoly \(\text{[Björkegren 2019]}\), are profitable under this competition policy. This suggests that there may be settings where competition can substitute for access regulation.

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 Table 4 rows 5-7, 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. It is the urban consumers who spend a fraction of their time in

only at the boundaries of the two networks, they do not adjust for these internal spillovers. 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.
rural areas who switch networks in response to tower investment (see Figure [A1]). 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 diagnostics 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 proliferation of false information.\textsuperscript{52} However, if consumers enjoy consuming fake news, then they are unlikely to switch to a competing network that is better monitored. In such an environment, competition is likely to reduce the investments of interest (though it may increase other investments).

9.4. Models that do not account for network structure grossly mischaracterize outcomes. I also assess the results that would be obtained under simpler demand systems.

\textit{If individuals make decisions independently (no ripple effects).} Nonnetwork models commonly treat individual decisions as independent, either explicitly or implicitly, by aggregating demand. I assess a modified equilibrium where each individual makes their decisions independently, ruling out ripple effects.\textsuperscript{53} Such a model grossly mischaracterizes results. Under this naive model, competition would induce the incumbent to lower prices only $1/3 \ (1/2)$ as far as it does under a full equilibrium, for the

\textsuperscript{52}For example, Presidential Candidate Elizabeth Warren said, “Imagine Facebook and Instagram trying to outdo each other to protect your privacy and keep misinformation out of your feed.”

\textsuperscript{53}Consumers believe that their contacts will adopt at the same month as they did at baseline, using the operator $\hat{a}_j(p, \phi_j, \phi_{\text{median}})$ that is optimal for calls to the median individual from their location.
Table 4. Return on Tower Investment under Different Competition Policies

<table>
<thead>
<tr>
<th>Equilibrium</th>
<th>Impact of Building Lowest Population Density Towers</th>
<th>ROI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prices</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incumbent</td>
<td>Entrant</td>
<td>Costs</td>
</tr>
<tr>
<td>$p_i^{\text{momo}}$</td>
<td>$p_e^{\text{momo}}$</td>
<td>$m$</td>
</tr>
<tr>
<td>Full Model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline monopoly</td>
<td>1.00, 1.00</td>
<td>-</td>
</tr>
<tr>
<td>With competitor, interconnection $0.11/min</td>
<td>0.70, 0.60</td>
<td>0.60, 0.50</td>
</tr>
<tr>
<td>...fixing operator</td>
<td>0.92, 0.88</td>
<td>1.23, 0.97</td>
</tr>
<tr>
<td>...additional effect of operator choice</td>
<td>0.51, 0.61</td>
<td>3.66, 3.72</td>
</tr>
<tr>
<td>With competitor, interconnection $0</td>
<td>0.40, 0.40</td>
<td>0.30, 0.20</td>
</tr>
<tr>
<td>...fixing operator</td>
<td>0.89, 0.78</td>
<td>0.68, 0.43</td>
</tr>
<tr>
<td>...additional effect of operator choice</td>
<td>0.67, 2.79</td>
<td>2.79, 6.22</td>
</tr>
<tr>
<td>Alternate Models</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partial Equilibrium*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>With competitor, interconnection $0.11/min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Ripple Effects:</td>
<td>0.70*, 0.60*</td>
<td>0.60*, 0.50*</td>
</tr>
<tr>
<td>Rewired Network:</td>
<td>0.70*, 0.60*</td>
<td>0.60*, 0.50*</td>
</tr>
</tbody>
</table>

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. Results under alternate models are partial adoption equilibrium, given price levels.
focal interconnection rate. This model also omits 20% (13%) of the welfare gains from competition. I also assess impact on incentives to invest, by imposing the equilibrium prices from the full model and then computing partial equilibrium results. The simpler model underestimates the incumbent’s subscriber revenue from building rural towers by 52% (56%) and the ROI by 54% (55%), as shown in Table 4 row 8.

If model captures patterns of links, but not explicit network structure. An alternate simplification would allow for ripple effects, but considers categories of links rather than the actual structure of the network (e.g., Ryan and Tucker, 2012). Collapsing the network in this way also mischaracterizes outcomes. I create a rewired graph $G'$ by replacing each link $ij$ with link $ij'$, with the same communication intensity (shock distributions $F_{ij'} = F_{ij}$), but where $j'$ is randomly selected from the set of nodes with the same baseline adoption date and final coverage as $j$ (capturing whether the individual is urban or rural). $G$ and $G'$ appear identical under representations that only consider patterns of links: individual $i$ is linked to the same number of similar nodes, with the same corresponding link intensities. But $G'$ jumbles the structures in the network: when equilibrium prices from the full model are imposed, this rewired network would result in the incumbent’s subscriber revenue from building rural towers being 86% larger and ROI 17% larger, in the low equilibrium (see Table 4 row 9).

These results suggest that approaches that do not consider explicit network structure can grossly mischaracterize economic outcomes in a network industry.

---

54 In these equilibria, the incumbent selects price 90% (80%) of monopoly price and the entrant 60%. See Supplemental Appendix.
55 To minimize computational costs I impose the equilibrium prices from the full model, and compute partial equilibrium incentives to invest under the modified model. Under a full equilibrium, the bias on investment incentives is likely to be more substantial.
56 That ripple effects are important was foreshadowed by the monopoly results, which find they account for a substantial fraction of the impact of price reductions. If the model were further simplified by being aggregated by location, it would additionally fail to capture the large business stealing effects from people who live in urban areas but sometimes travel to rural areas.
57 I match based on discretized final coverage in 10 bins.
9.5. Additional Results.

Asymmetric interconnection rates give regulators finer control. A regulator could tilt favor towards a smaller network by allowing it discounted access to the larger network. Or, a regulator may wish to allow a larger network to charge a higher rate to offset foregone network effects from investment. 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) (as shown in Table A3 rows 6 and 7).

Number portability increases the level of competition. 25% of developing country regulators have introduced policies that allow consumers to port their phone numbers between operators; 15% were planning to do so in the future (GSMA, 2013). Switching costs have theoretically ambiguous effects on network competition (Farrell and Shapiro, 1988; Suleymanova and Wey, 2011; Chen, 2016). My consumer survey suggests that number portability would lower the cost of switching operators from $36.09 to $18.51. I simulate a competitive equilibrium with this switching cost, and find more intense price competition in the lower equilibrium, which lowers incumbent profits. This suggests that given the choice, the incumbent would elect to maintain high switching costs. The policy boosts consumer surplus, by different amounts in the low and high equilibria: +$159m (+$1m) (Shown in Table A3 second to last row.)

9.6. Robustness. In the baseline case, the government eventually allowed Operator C to enter (in the end of 2009). I simulate similarly delaying the entry of the competitor until July 2008 (5 months before the end of the horizon). The entrant sets lower prices (40% (30%) of the monopoly level), the incumbent keeps prices weakly

---

5831% 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.

59This large distinction between the two equilibria would likely to be muted if prices were evaluated on a finer grid.

60Before the entry date, subscribers may select only the incumbent \( a_{it} \equiv 0 \) for \( t < t_{\text{entry}} \); after that date, they may select either \( a_{it} \in \{0, 1\} \) for \( t \geq t_{\text{entry}} \).
higher (70% of the monopoly level), and the total impact on welfare is smaller (shown in Table A3 last row).

The Supplemental Appendix assesses several alternate specifications. Results are similar under different time horizons. Under a longer horizon through period \( T \) with that final period then repeated for 3 years, competition increases ROI even for lower interconnection rates. Results are similar to the main results under different draws of the random preferences \([\eta_i^1, \bar{\eta}_i^1]\), and under entrant favoring equilibria. If at the point of adoption, consumers exactly anticipate which operators their contacts will select \((\hat{a}_j ≡ a_j)\), consumer decisions are no longer guaranteed to reach equilibrium, but outcomes are similar under an approximate notion of equilibrium. If the incumbent moves before the entrant, results are similar, but are less stable for this grid of prices.

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. 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 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. 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.

References

to Improve Rwandan Competitiveness,”.


White Paper.

Phone Discount,”.


CHEN, J. (2016): “How Do Switching Costs Affect Market Concentration and Prices in


FACCIO, M. AND L. ZINGALES (2017): “Political Determinants of Competition in the Mobile
Research.

FARR, T. G., P. A. ROSEN, E. CARO, R. CRIPPEN, R. DUREN, S. HENSLEY, M. KO-
BRICK, M. PALLER, E. RODRIGUEZ, L. ROTH, D. SEAL, S. SHAFFER, J. SHIMADA,

FARRELL, J. AND P. KLEMPERER (2007): “Chapter 31 Coordination and Lock-In: Compe-
tition with Switching Costs and Network Effects,” in Handbook of Industrial Organization,

RAND Journal of Economics, 19, 123–137.

FCC (2011): “Connect America Fund & Intercarrier Compensation Reform Order and FN-
PRM Executive Summary,”.

in mobile communications,” Economic Policy, 33, 45–100.


GOOLSBEE, A. AND P. J. KLENOW (2002): “Evidence on Learning and Network External-


GSMA (2013): “Majority of developing world mobile markets have no plans for MNP,”.


KIMBALL, S. (2019): “Mark Zuckerberg dismisses co-founder’s call to break up Facebook,”


LAZAUSKAITE, V. (2009): “Mobile Termination Rates: To Regulate or Not To Regulate,”


PWC (2011): “Rwanda Interconnection Costing Model,”


REUTERS (2017): “Report recommends Safaricom should be broken up: Business Daily,”


Table A1. Competitive Interaction: Interconnection 8011 Switching Cost $36 Low Equilibrium

<table>
<thead>
<tr>
<th>Incumbent</th>
<th>Entrant</th>
<th>Profit</th>
<th>Profit</th>
</tr>
</thead>
<tbody>
<tr>
<td>10pct</td>
<td>20pct</td>
<td>30pct</td>
<td>40pct</td>
</tr>
<tr>
<td>10pct</td>
<td>20pct</td>
<td>30pct</td>
<td>40pct</td>
</tr>
</tbody>
</table>

Best responses are bolded. Underlined cell represents a subgame perfect equilibrium when the entrant moves first.

Table A2.

<table>
<thead>
<tr>
<th>Incumbent</th>
<th>Entrant</th>
<th>Profit</th>
<th>Profit</th>
</tr>
</thead>
<tbody>
<tr>
<td>10pct</td>
<td>20pct</td>
<td>30pct</td>
<td>40pct</td>
</tr>
<tr>
<td>10pct</td>
<td>20pct</td>
<td>30pct</td>
<td>40pct</td>
</tr>
</tbody>
</table>

Best responses are bolded. Underlined cell represents a subgame perfect equilibrium when the entrant moves first.
<table>
<thead>
<tr>
<th>Coverage</th>
<th>Incumbent/Price</th>
<th>10pct</th>
<th>20pct</th>
<th>30pct</th>
<th>40pct</th>
<th>50pct</th>
<th>60pct</th>
<th>70pct</th>
<th>80pct</th>
<th>90pct</th>
<th>Full</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build all towers</td>
<td>20pct</td>
<td>42, -40</td>
<td>20, -1</td>
<td>20, -2</td>
<td>20, -2</td>
<td>20, -2</td>
<td>20, -2</td>
<td>20, -2</td>
<td>20, -2</td>
<td>20, -2</td>
<td>20, -2</td>
</tr>
<tr>
<td>Build all towers</td>
<td>30pct</td>
<td>60, -54</td>
<td>68, -28</td>
<td>55, -1</td>
<td>55, -2</td>
<td>55, -2</td>
<td>55, -2</td>
<td>55, -2</td>
<td>55, -2</td>
<td>55, -2</td>
<td>55, -2</td>
</tr>
<tr>
<td>Build all towers</td>
<td>40pct</td>
<td>53, -55</td>
<td>72, -29</td>
<td>84, -13</td>
<td>78, -1</td>
<td>78, -2</td>
<td>78, -2</td>
<td>78, -2</td>
<td>78, -2</td>
<td>78, -2</td>
<td>78, -2</td>
</tr>
<tr>
<td>Build all towers</td>
<td>50pct</td>
<td>41, -47</td>
<td>58, -22</td>
<td>79, -7</td>
<td>92, -5</td>
<td>97, -1</td>
<td>97, -2</td>
<td>97, -2</td>
<td>97, -2</td>
<td>97, -2</td>
<td>97, -2</td>
</tr>
<tr>
<td>Build all towers</td>
<td>60pct</td>
<td>32, -43</td>
<td>43, -13</td>
<td>61, 4</td>
<td>82, 5</td>
<td>104, 2</td>
<td>114, -2</td>
<td>115, -2</td>
<td>115, -2</td>
<td>115, -2</td>
<td>115, -2</td>
</tr>
<tr>
<td>Build all towers</td>
<td>70pct</td>
<td>26, -39</td>
<td>33, -7</td>
<td>44, 15</td>
<td>60, 19</td>
<td>57, 17</td>
<td>63, 11</td>
<td>65, 11</td>
<td>67, 11</td>
<td>69, 11</td>
<td>71, 11</td>
</tr>
<tr>
<td>Build all towers</td>
<td>80pct</td>
<td>20, -37</td>
<td>26, -3</td>
<td>33, 22</td>
<td>44, 31</td>
<td>62, 35</td>
<td>92, 26</td>
<td>113, 9</td>
<td>127, -2</td>
<td>127, -2</td>
<td>127, -2</td>
</tr>
<tr>
<td>Build all towers</td>
<td>90pct</td>
<td>16, -35</td>
<td>20, 0</td>
<td>25, 26</td>
<td>32, 39</td>
<td>44, 47</td>
<td>63, 47</td>
<td>89, 29</td>
<td>116, 9</td>
<td>128, -2</td>
<td>128, -2</td>
</tr>
<tr>
<td>Build all towers</td>
<td>Full</td>
<td>13, -34</td>
<td>16, 2</td>
<td>19, 30</td>
<td>24, 44</td>
<td>32, 56</td>
<td>44, 60</td>
<td>60, 50</td>
<td>86, 31</td>
<td>116, 7</td>
<td>126, -1</td>
</tr>
<tr>
<td>Don’t build last 34 rural towers</td>
<td>10pct</td>
<td>-22, -1</td>
<td>-21, -2</td>
<td>-21, -2</td>
<td>-21, -2</td>
<td>-21, -2</td>
<td>-21, -2</td>
<td>-21, -2</td>
<td>-21, -2</td>
<td>-21, -2</td>
<td>-21, -2</td>
</tr>
<tr>
<td>Don’t build last 34 rural towers</td>
<td>20pct</td>
<td>43, -40</td>
<td>21, -1</td>
<td>21, -2</td>
<td>21, -2</td>
<td>21, -2</td>
<td>21, -2</td>
<td>21, -2</td>
<td>21, -2</td>
<td>21, -2</td>
<td>21, -2</td>
</tr>
<tr>
<td>Don’t build last 34 rural towers</td>
<td>30pct</td>
<td>56, -53</td>
<td>67, -27</td>
<td>56, -1</td>
<td>56, -2</td>
<td>56, -2</td>
<td>56, -2</td>
<td>56, -2</td>
<td>56, -2</td>
<td>56, -2</td>
<td>56, -2</td>
</tr>
<tr>
<td>Don’t build last 34 rural towers</td>
<td>50pct</td>
<td>34, -45</td>
<td>52, -21</td>
<td>73, -4</td>
<td>91, -4</td>
<td>97, -1</td>
<td>97, -2</td>
<td>97, -2</td>
<td>97, -2</td>
<td>97, -2</td>
<td>97, -2</td>
</tr>
<tr>
<td>Don’t build last 34 rural towers</td>
<td>60pct</td>
<td>24, -39</td>
<td>36, -9</td>
<td>54, 7</td>
<td>76, 10</td>
<td>102, 3</td>
<td>114, 1</td>
<td>114, 2</td>
<td>114, 2</td>
<td>114, 2</td>
<td>114, 2</td>
</tr>
<tr>
<td>Don’t build last 34 rural towers</td>
<td>70pct</td>
<td>18, -37</td>
<td>25, -3</td>
<td>36, 19</td>
<td>53, 23</td>
<td>80, 22</td>
<td>111, 9</td>
<td>122, 2</td>
<td>122, 2</td>
<td>122, 2</td>
<td>122, 2</td>
</tr>
<tr>
<td>Don’t build last 34 rural towers</td>
<td>80pct</td>
<td>14, -35</td>
<td>18, 1</td>
<td>25, 27</td>
<td>36, 35</td>
<td>54, 40</td>
<td>84, 32</td>
<td>111, 10</td>
<td>126, 2</td>
<td>126, 2</td>
<td>126, 2</td>
</tr>
<tr>
<td>Don’t build last 34 rural towers</td>
<td>90pct</td>
<td>11, -34</td>
<td>14, 3</td>
<td>17, 30</td>
<td>24, 44</td>
<td>36, 53</td>
<td>55, 52</td>
<td>81, 35</td>
<td>113, 10</td>
<td>127, 2</td>
<td>127, 2</td>
</tr>
<tr>
<td>Don’t build last 34 rural towers</td>
<td>Full</td>
<td>9, -33</td>
<td>10, 5</td>
<td>13, 33</td>
<td>16, 49</td>
<td>24, 62</td>
<td>36, 66</td>
<td>51, 56</td>
<td>78, 37</td>
<td>114, 9</td>
<td>125, -2</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Policy</th>
<th>Outcomes (January 2005-December 2008)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inter-</td>
</tr>
<tr>
<td></td>
<td>connect</td>
</tr>
<tr>
<td>Baseline Monopoly</td>
<td>-</td>
</tr>
</tbody>
</table>

**Impact of adding additional competitor**

**Entering January 2005**

- **Joint profit maximizing**
  - 0.33, 0.43 ↔ 36
  - 0.80, 0.90 0.80, 0.90 +1, +2 -1, -1 +4, +2 +69, +32
- **Inc. profit maximizing**
  - 0.33 ↔ 36
  - 0.80, 0.90 0.80, 0.90 +2, +1 -1, -1 +4, +2 +69, +32
- **Focal**
  - 0.11 ↔ 36
  - 0.70, 0.60 0.60, 0.50 -10, -23 +5, +2 +4, +2 +113, +171
- **Initial level** (RURA, 2006)
  - 0.09 ↔ 36
  - 0.50, 0.60 0.40, 0.50 -28, -27 -0, +7 +1, +2 +222, +171
- **Revised level** (PwC, 2011)
  - 0.07 ↔ 36
  - 0.50, 0.50 0.40, 0.40 -31, -43 +3, +4 +1, -2 +222, +217
- **Bill and keep**
  - 0.00 ↔ 36
  - 0.40, 0.40 0.30, 0.20 -62, -99 +13, +15 -3, -11 +272, +330
- **Asymmetric: to incumbent**
  - 0.04 ↔ 36
  - 0.40, 0.40 0.30, 0.30 -55, -68 +6, +12 -3, -4 +272, +293
  - 0.07 →
- **Asymmetric: to entrant**
  - 0.07 ↔ 36
  - 0.70, 0.60 0.60, 0.50 -10, -28 +5, +7 +4, +2 +113, +171
  - 0.04 →

**Entering July 2008**

- **Focal**
  - 0.11 ↔ 19
  - 0.50, 0.60 0.50, 0.50 -20, -26 -1, +5 +3, +2 +215, +172

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. ↔ indicates symmetric interconnection rate; ← indicates rate charged to entrant for connecting to incumbent; → 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**

This section follows Björkugren (2019).

**Identification.** Traditional approaches towards network goods estimate the value of each connection indirectly, based on correlations in adoption. For example, consider
The incumbent dominates market share among rural users; the entrant attracts away urban users. When the incumbent builds rural towers (changing the rollout plan from $z(50\%)$ to $z(100\%)$), it induces the highlighted marginal group of users to switch from the entrant to the incumbent. These marginal users spend most but not all of their time in urban areas, with the remainder in rural areas. Interconnection rate $0.11/\text{min}$, low equilibrium, incumbent favoring (the high equilibrium is visually indistinguishable).

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:

$$A_i = I (\theta_{ij} A_j + \eta_i^0 \geq p_{t}^{\text{handset}})$$

where $\theta_{ij}$ is the value of the link if $j$ also adopts. It is difficult to estimate $\theta_{ij}$ 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.$^{61}$

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

$$\theta_{ij} = E u_{ij} (p_t^0, \phi_t^0)$$

$^{61}$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.
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 ($\epsilon_{ijt}$) is uncorrelated with costs ($p_i^0$ and $\phi_{ij}^0\phi_{jt}^0$, 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. Apart from these restrictions, communication shocks can be arbitrarily correlated between any links in the network.

After the network portion of utility ($\theta_{ij}$) is estimated, it is straightforward to back out any residual heterogeneity affecting adoption, $\eta_i^0$. 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 ($\gamma$ and $\alpha$), and how usage responds to cost ($\beta_{\text{cost}}$ and $\beta_{\text{coverage}}$). 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:

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

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

\[\text{I evaluate whether the duration of calls across a link changes with the time since an individual adopted, or as more of the sender’s and receiver’s contacts join the network, after controlling for cost. For the median subscriber, the change in duration associated with either time, or the change in the number of that individual’s contacts on the network is less than 5% of the change associated with the changes in prices and coverage over this time period. See Supplemental Appendix.}\]
communication. It suggests that an individual will not call across a link if the shock is too low relative to the cost (affected by $\alpha$ 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 $\epsilon$:

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

given coverage under the baseline rollout plan $\phi_t(z_0)$. 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 $F_{ij}[\epsilon(1 \text{ second}, \ldots)]$. The likelihood of calls of total duration $d_{ijt}$ is $F_{ij}[\epsilon(d_{ijt} + 1, \ldots)] - F_{ij}[\epsilon(d_{ijt}, \ldots)]$.

These are combined into the log-likelihood function:

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

$$+ \left[ 1 - 1_{\{\text{call placed}_{ijt}\}} \right] \ln F_{ij}[\epsilon(1 \text{ second}, pt, \phi_{it}, \phi_{jt})]$$

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 ($\gamma$, $\alpha$, $\beta_{cost}$, $\beta_{coverage}$). I allow the parameter scaling the shock distribution ($\sigma_i$), 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.\footnote{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 $\mu_{ij} = \mu_i + \mu_{\max(x_i,x_j),\phi_{it}\phi_{jt}}$, which includes an individual mean term $\mu_i$, and a cost fixed effect for each combination of link adoption date ($\max\{x_i,x_j\}$) and average coverage ($\phi_{it}\phi_{jt}$), discretized to 519 combinations. See Björkegren (2019).}
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, $\eta_i^0$. 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 $E_{x_i}U_i^{0,x_i}(x_{G_i}, 0) \geq E_{x_i}U_i^{0,x_i+K}(x_{G_i}, 0)$. 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:

$$E_{x_i}U_i^{0,x_i}(x_{G_i}, 0) + (1 - \delta^K)\eta_i^0 \geq \delta^K E_{x_i}p_{x_i+K} - E_{x_i}U_i^{0,x_i+K}(x_{G_i}, 0)$$

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

$$E_{x_i-K}U_i^{0,x_i-K}(x_{G_i}, 0) + (1 - \delta^{\tilde{K}})\eta_i^0 \leq \delta^{\tilde{K}} E_{x_i-K}p_{x_i+K} - \delta^{\tilde{K}} E_{x_i-K}U_i^{0,x_i-K+\tilde{K}}(x_{G_i}, 0)$$

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:

$$\underline{\eta}_i^0 = \frac{1}{1 - \delta^K} \left[ p_{x_i} - \delta^K E_{x_i}p_{x_i+K} - \sum_{s=0}^{K-1} \delta^s E_{x_i}u_{x_i+s}(p_{x_i+s}, \phi_{x_i+s}, x_{G_i}, 0) \right]$$

$$\bar{\eta}_i^0 = \max_{K > 0} \frac{1}{1 - \delta^K} \left[ p_{x_i-K} - \delta^K E_{x_i-K}p_{x_i-K+\tilde{K}} - \sum_{s=0}^{K-1} \delta^s E_{x_i-K+s}(p_{x_i-K+s}, \phi_{x_i-K+s}, x_{G_i}, 0) \right]$$

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.
I set $K = 2$ months\textsuperscript{65}. Note that the future after $x_i + \max(K, \bar{K} - K)$ 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\textsuperscript{66} 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 $\eta_0^{i}$‘s for 0.8m nodes adopting between $x_i \in [K, T - K]$\textsuperscript{67}.

Validation. In a robustness check, \textsuperscript{Björkgren (2019)} finds that the value implied by calls corresponds with the value implied by adoption, using moment inequalities analogous to Equations 7 and 8. See Supplemental Appendix for more details.

\textsuperscript{65}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.

\textsuperscript{66}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 \textsuperscript{Björkgren (2019)}.

\textsuperscript{67}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.