COMPETITION IN NETWORK INDUSTRIES:
EVIDENCE FROM MOBILE TELECOMMUNICATIONS IN RWANDA

DANIEL BJÖRKEGREN*

Many modern technologies have network effects, and as a result lead to industries with natural monopolies. How should societies discipline these industries? This paper analyzes the scope for competition to affect welfare and investment in the Rwandan mobile phone network during a 4.5 year period of dramatic growth. I use transaction data from nearly the entire network of Rwandan mobile phone subscribers at the time. I use the method and estimates of Bjorkegren (2017), which identifies the value of network effects based on usage after adoption. The Rwandan government delayed the entry of competition to allow the incumbent to recoup its investment. I evaluate what would have happened had competition been introduced at an earlier stage of the network's growth. The benefits of investment were highly dispersed: at baseline, only 25% of the revenue from building the rural tower network came from rural subscribers; the rest would have been split with a competitor. Despite this, preliminary results suggest that the incumbent would have still chosen to build the rural network had a competitor been added. Adding a competitor would have lowered prices, and increased net welfare by amount equivalent to 1% of GDP or 5% of official development aid to Rwanda over this time period.

Preliminary and incomplete; please do not circulate.

JEL Classification Codes: O33, L96, O180, L51

Keywords: network goods, infrastructure, information technology

---

*Brown University. E-mail: danbjork@brown.edu, Web: http://dan.bjorkegren.com
Revision February 20, 2018.
Thank you to Nathan Eagle for providing access to the data, computing facilities, and helpful conversations. Thank you also to Susan Athey and Jesse Shapiro. In Rwanda, I thank the staff of my telecom partner, RURA, NISR, and PSF for helpful conversations and access to data. Aaron Weisbrod provided excellent research assistance. Thank you to feedback from audiences at UCSD,

1. Introduction

Many modern technologies have network effects, and as a result lead to industries with natural monopolies. How should societies discipline these industries?

Historically, the question of how to discipline network industries has not extended much further than the technologies themselves (consider telecommunications: AT&T, payment systems, operating systems: Microsoft, search engines: Google, social networks: Facebook). However, as software has become more embedded in the economy, it has generated network effects in disrupted industries, and the question has followed (for example, how should societies manage Uber and Airbnb, whose market positions rely heavily on network effects?).

An indirect approach would be to accept that market power arises from network effects, and regulate the industry to mitigate its consequences. However, there are substantial drawbacks to broadly regulating innovative industries. First, these industries change rapidly: the dominance in operating systems that Microsoft held matters much less today, now that web services have replaced the role of many software packages. In such environments, governments are forced to intervene either ex ante in a blunt manner, or ex post in a reactive manner. But these products also require large investments, made on the expectation of future profits under anticipated regulatory regimes. Even if reactive policy improves a particular market ex post, it can generate uncertainty that may stifle investment in the same market—or in others.

An alternative approach is to discipline the industry with competition. When competition does not naturally arise, governments can intervene to induce it. Regulation can directly intervene on the shape of network effects (e.g., requiring compatibility between competing systems) or force a change in market structure (breaking up a dominant firm like Microsoft). But it is not clear how much competition governments should induce. When a network is split among competitors, firms are likely to underinvest because each internalizes only a fraction of network effects. To encourage investment, governments often tolerate monopoly provision while a network is expanding, and then tilt regulation to promote competition as the market matures.

University College London, Berkeley-Stanford IO Fest, UW, and Microsoft Research. This work was supported by Brown University SSRI, the NET Institute (http://www.netinst.org), and the W. Glenn Campbell and Rita Ricardo-Campbell National Fellowship at Stanford University.

But there are many ways to tilt the playing field. How, and how strongly should societies promote competition in emerging network goods?

While theory provides intuition about network effects, there is little empirical work to guide policy.[1] Because of the impact on expectations around future investment, it is not sufficient to just analyze the outcome of a particular market after a reactive policy. And these markets have been difficult to study at the micro level. It is hard to identify network effects: one individual may adopt after a nearby individual because the individual provides network benefits, or because connected individuals share similar traits or are exposed to similar environments. Additionally, network effects are often extremely dispersed, but it is costly to measure an entire network using traditional data sources. A marginal user of Microsoft Office increases the benefits of using the software package for those she would collaborate with, who in turn may use the software more, resulting in benefits that ripple throughout the network of potential users. The actual network of users matters even for many goods where network effects are indirect—for example, dynamic carpooling services like UberPool become more useful when others traverse your same route; Tesla's autopilot learns from other Teslas that drive your same roads. In order to understand the effect of an intervention into these markets, one would have to measure and predict all of the ripple effects across these actual networks.

In Bjorkegren (2017), I overcome these limitations by analyzing the benefit provided by each communication link during the rollout of a developing country phone network. I use 5.3 billion transaction records from Rwanda's dominant mobile phone operator, which held over 88% of the market, during a period of dramatic expansion. I exploit several features of this market.

First, while typical network industries have complex interactions with substitutes (e.g., various technologies could serve as substitutes for parts of Facebook: e-mail, listservs, photo sharing apps, blogs, newspapers), in Rwanda at this time, a handful

[1]Early theoretical work includes Rohlfs (1974), Katz and Shapiro (1985), and Farrell and Saloner (1985). More recent work includes Fainmesser and Galeotti (2015) and Fainmesser and Galeotti (2016). Most empirical work on network goods measures the extent of network effects; see for example Saloner and Shepard (1995), Goolsbee and Klenow (2002), and Tucker (2008). Ryan and Tucker (2012) uses a method which has some similarity to mine; it estimates the adoption of a videoconferencing system over a small corporate network, and evaluates policies of seeding adoption.

of radio stations were essentially the only alternative for remote communication.[2] This means that my data includes nearly all relevant interactions over the relevant network.

Second, I observe every connection between subscribers, as well as the calls placed across each connection. This allows me to overcome identification problems associated with network effects. I overcome simultaneity in consumer adoption decisions by inferring the value generated by each connection from subsequent interaction across that connection. This provides a direct measure of value: a subscriber must value a connection at least as much as the cost of calls placed across it.[3] Further, because the firm changed calling prices and increased the quality of service, I can identify the underlying demand curve for communication across each link.

Third, detailed industry data is available because of engineering and regulatory features of the market. Because mobile telephone systems were first rolled out in developed country markets, by the time voice networks were rolled out in Africa, much of the engineering was standardized. Further, existing landline phone regulators had a mandate to collect detailed information from mobile operators. To determine the cost of expanding or shrinking the network, this paper uses a detailed engineering cost model used by the regulator, populated with extensive cost data from operators and crosschecked against international benchmarks.

Bjorkegren (2017) exploits the first two features to develop a structural model of adoption under monopoly provision of the mobile phone system. This paper extends this model to simulate the effect of competition.

Developing country phone systems are not only a convenient setting to study competition in network goods, they are also an important setting. The details of competition policy have been 'a main bottleneck' in the development of African telecom markets (World Bank, 2004). Additionally, these phone networks are still expanding, and they are the distribution system for emerging services that require additional

[2]The fixed line network is small (with penetration below 0.4%), and mail service is insignificant: the average mail volume per person was 0.2 pieces per year in Rwanda, relative to 2.4 pieces in Kenya and 538.8 pieces in the US (Sources: National Institute of Statistics Report 2008, Communications Commission of Kenya, U.S. Postal Service 2011, U.S. Census).

[3]In contrast, most empirical studies of network goods use coarse measures of the value of joining the network; exceptions that use individuals' local network are Tucker (2008) and Birke and Swann (2010).

investment, including mobile money and mobile internet.[4] Competition policy as a result remains hotly contested: regulators that heavily pushed competition are now deciding how to manage increasing calls for consolidation (Moody's, 2015).

While extensive theoretical work has been done on competition policy for developed country landline networks (Armstrong, 1998; Laffont et al., 1998; Laffont and Tirole, 2001), it can be inconclusive (Vogelsang, 2013) and provides limited guidance for developing countries mobile networks. It was developed during the liberalization of established landline networks, and generally omits factors important for growing networks, such as investment and network effects (with few exceptions; e.g., Valletti and Cambini, 2005).

Traditional econometric approaches also provide limited policy guidance. The most straightforward approach would analyze investment in countries that have changed telecom policies over time (Faccio and Zingales, 2017). However, that exercise is difficult to interpret, because firms take into account expected future policy when investing: the same policy change could induce either an immediate increase or decrease in investment, depending on whether it was more or less than expected. Also, it is difficult to directly study network effects in competitive markets: data from a single firm would only provide information on a portion of the network. Since it would cover only communication with that firm's subscribers, it would be selected directly based on consumer preferences. In a competitive market, data would need to be obtained from competitors covering most of the network, in a form that allowed individuals to be linked across firms.

My approach overcomes these challenges with two steps.

First, I estimate a demand model of the Rwandan mobile phone market under monopoly conditions, prior to the network being split by competition. Because the system was operated by a near monopolist, I observe nearly all of the mobile phone subscribers at the time of my data: my sample is less selected. Because I carefully

[4]Competition policy appears to be first order for the development of mobile money networks. Developing a network of rural agents is costly, and an operator may only do so if it captures large benefits elsewhere in its network. Indeed, the most successful implementations of mobile money have been by dominant telecoms in concentrated markets; telecom competitiveness is actually correlated with lower agent density.

model consumer and firm objective functions, I can directly measure investment incentives. And my data covers a long time period with substantial variation in prices and coverage, which include conditions similar to what may have been observed had a competitor entered earlier.

Second, I extend the model to evaluate the effects of increasing competition. Competition could introduce subtle changes in the market not visible under monopoly provision. I discipline the exercise using three sources of data. First, to recover additional parameters of choice under competition, I survey Rwandan consumers on hypothetical choices that mimic the choices they would make in my counterfactuals. While hypothetical scenarios do not always reveal true preferences, they can be effective predictors of behavior (Bernheim et al., 2013). I corroborate these estimates by posing a validation hypothetical choice that resembles a real choice observed in my data (the choice of mobile plan). Second, I consider the plans and consumer behavior that resulted when competition ultimately was introduced to Rwanda, using data from firms, the regulator, and my consumer survey. Finally, I consider the plans and consumer behavior in comparable African markets that were competitive at this time.

This approach has limitations. In particular, my data includes only individuals who subscribed by 2009 under monopoly provision. In a competitive counterfactual, prices may be lower, which could cause individuals who are not in my data to adopt earlier. However, I can still simulate the market for the earlier period of the network, say 2005-2007, as long as adoption does not become more attractive in those years under competition than it was under the monopoly in 2009. I also bound the behavior of the omitted part of the network using data from a representative household survey.

Rwanda initially granted a time-limited monopoly to its first cellular operator. I simulate allowing a competitor to enter earlier, and compute the resulting changes in coverage, prices, and welfare. During the period I observe the incumbent operator (2005-2009), it made large investments in rural areas, increasing coverage from 60% to 95% of land area. At the end of 2009, its first effective competitor was granted a license.[5] It built out less coverage, charged lower prices, and within two years

[5] In 2005, a second license was granted, but to an ineffectual competitor that had management issues. Its ownership changed three times and its license was eventually revoked. Through this period the incumbent maintained over 88% market share.

captured a third of the market. If the competitor had been granted a license earlier, how would the industry have developed? Would coverage still have expanded into rural areas?

I extend the model developed in Bjorkegren (2017) to allow each consumer to choose both an adoption date and operator. The two firms each choose a path of calling prices and a tower rollout plan from a menu. I find a competitive equilibrium in these strategies, and measure outcomes.

I use several simplifications to make simulation tractable: consumers can choose one operator when they adopt (no multihoming). I also make restrictions on operators. As a condition for receiving a license, the Rwandan regulator required firms to submit a rollout plan. I require firms to commit to a rollout plan, as well as a path of prices, at the beginning of the license period. Also, to limit the multiplicity of equilibria, I do not allow firms to charge different rates for off-network calls. These operator restrictions can be considered the terms of competition set by the regulator.

My findings are as follows [preliminary]:

First, the benefits to building the network are extremely dispersed. Only 25% of the revenue from building the rural tower network came from rural subscribers. As a result, the revenue generated by building the rural network came in large part from urban subscribers. Competition is likely to split the lucrative urban market, and thus has the potential to reduce incentives to invest.

However, I find that the revenue generated by building the rural network was large enough that, in this case, the incumbent would still have have sufficient incentives to build the rural network had an additional competitor been added.

Second, adding a competitor would have lowered prices by 40%, and increased the net welfare provided by the mobile phone system by approximately 36%. This increase in net welfare is equivalent to 1% of GDP or 5% of official development aid over this time period. This is despite the fact I study an early period, where few Rwandans had mobile phones (3-15% of the population), and the network provided voice service but not mobile internet or mobile money. (This earlier incarnation provides a clean setting to demonstrate my method.) These results suggest that even in the world's poorest economies, the industrial organization of emerging technologies can have large welfare implications.

I also find that competition would have been unlikely to develop in absence of interconnection regulation. If the incumbent chose the terms of interconnection, it would price its the entrant out, and no competition would develop. This result echoes what is seen in many network industries: for example, Facebook dictates the terms of interconnection with rival platforms, and carefully restricts access to preserve its network.

The next section describes the development of competition in mobile phone networks worldwide and in Rwanda. Section 3 describes the data. Section 4 presents a model of phone adoption and usage. Section 5 describes estimation, Section 6 presents monopoly benchmarks, Section 7 describes the applicability of the model to competition, and Section 8 describes the results of introducing competition. Section 9 concludes.

2. Context

Developing Country Phone Systems. In order to provide wireless phone service, a firm must use electromagnetic spectrum. To prevent interference, governments typically manage property rights over electromagnetic spectrum and sell licenses for approved uses. Upon securing rights to spectrum, a firm could roll out its own telephone network. However, a new telephone network is much more useful if it allows users to call other, existing networks. The first mobile network in a region typically negotiates terms to connect with the existing landline network. While most developed countries already had widespread landline networks, in developing countries most existing networks were small or insignificant. Because most people adopting a phone were new adopters, network effects have been much more important for consumer adoption in developing country systems. And they have become more important: unlike landline phones and early mobile phones, modern handsets can interact with new services that also have network effects (feature phones support mobile money, and smartphones support the internet and network apps such as Uber).

To connect to a landline phone network, an individual would have to connect a physical wire. Since it would be costly to connect physical wires to multiple networks, households would typically have one wire connected to a monopoly landline network. Historically, operators were disciplined through regulation, and then a particular form of competition after these markets were liberalized.

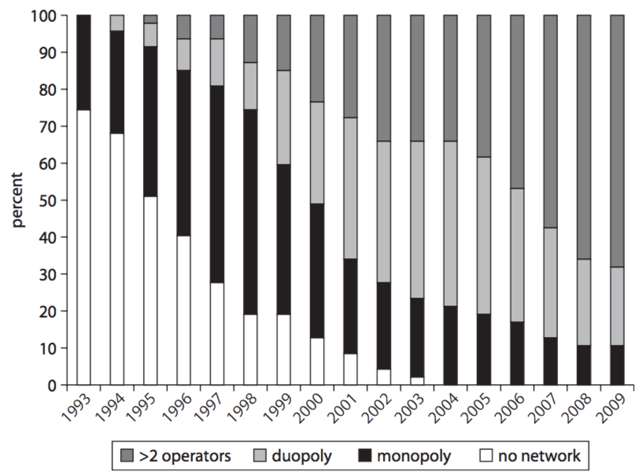
Because cellular signal blankets an entire area, it is feasible to reach the same household with multiple wireless networks. As a result, competition can take more flexible forms. Countries quickly realized that it may be possible to obtain better performance from the sector by allowing multiple operators to compete in providing service to end users.

However, an entrant mobile phone network will be of limited use unless it can connect to the incumbent mobile phone system. Left to the market, incumbents have typically demanded prohibitively high fees for interconnection, preventing competition. Thus regulators typically must intervene and determine the terms of interconnection. Economic theory suggests that regulation is necessary to get a small entrant off the ground (the 'one way' access problem). After competition develops, theory suggests that the problem is lessened ('two way' access) but that negotiated interconnection rates can be an instrument of collusion, so that ongoing regulation is required (Armstrong, 1998; Laffont et al., 1998). Theory suggests that interconnection rates should be set to a function of the cost of connecting a phone call; World Bank (2004) has produced a model for calculating these costs which is used as a benchmark in many countries. However, the regulator must continually decide which direction to tilt competitive favor. Different theoretical models suggest different optimal interconnection rates. Most focus on developed country systems where network effects are less important. Thus regulators face two large questions: how to shape the competitive landscape, and how much competition to promote?

After resolving initial interconnection disputes, most countries have slowly invited competition (see Figure 1), first over voice service and then over new services like data. But there have been increasing calls for consolidation; and in East Africa between 2010 and 2015, only one country saw net entry of a telecom operator (Uganda) while three countries had net exit (Burundi, Kenya, and South Sudan).

FIGURE 1. Telecom Competition

Figure 1.1 Competition in Mobile Markets in Sub-Saharan Africa, 1993–2009
percentage of countries with no provider, one provider, two providers, and three or more providers



Sources: ITU (2010), regulators, operators.

Source: Williams et al. (2011)

There is also little consensus on the optimal ground rules for competition. Table 1 summarizes current industry statistics and regulations in sub-Saharan Africa. While most countries regulate retail and interconnection prices, they consider different information to determine levels, and allow different amounts of complexity. In all surveyed countries, operators share some infrastructure, but the scope of sharing differs. In some, operators shared voluntarily, and in others they are compelled by government mandates.

Rwanda. In the aftermath of the 1994 genocide and civil war, the Rwandan government worked to develop a mobile phone system. In 1998 they granted a license to a multinational to develop and run a network (Operator A); it was understood that this license would be exclusive for a limited period of time. In 2003, the government announced it would provide a license to a second operator, which entered the market in 2005 (Operator B). The second operator sought to connect its network to the first; the resulting dispute over interconnection was "the major problem" at the regulatory agency at the time (RURA, 2005, 2006). In 2006, a consultant was hired to implement the World Bank Long Run Incremental Cost model. Despite the resolution

Table 1. Mobile Telecommunications in Sub-Saharan Africa

Industry Statistics (2015 or latest available)	Mean	SD
Number of operators	3.27	1.48
Top market share	0.58	0.19
Second highest market share	0.32	0.09
Market concentration (HHI)	0.49	0.21
Regulations*		
Retail prices are regulated	89.2%	
...based on costs	43.2%	
...based on benchmarks	37.8%	
Interconnection charges are regulated	97.1%	
...based on costs (LRIC or FDC)	71.4%	
...based on benchmarks	42.9%	
...asymmetrically between operators	30.8%	
...using multiple zones	34.1%	
...using multiple timebands	56.1%	
Infrastructure is shared	100%	
...by mandate	61.9%	
...including active infrastructure (electronics)	47.6%	

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.

of the interconnection dispute, this second operator was troubled and unsuccessful: after several changes in ownership (including by part of the Libyan government) it aggressively lowered prices and reached a maximum of 20% of market share for a brief period after the end of my data, and in 2011 its license was revoked for failure to meet obligations. In an effort to push competition, the Rwandan regulator granted a license to a third operator (Operator C), which entered the market at the end of 2009 with aggressive promotional prices as it rolled out a network. See Figure 2a for the evolution of on-network prices in Rwanda.

As Operator C rolled out its network, the Rwandan government wanted to avoid duplication of infrastructure. It required operators to share infrastructure when possible, by allowing others to install equipment on their towers, at prices set by the owning network. These terms of sharing led to a dispute between Operator A (who was willing to share at high prices) and Operator C (who wanted to pay low prices). In response, the government conducted a cost study, and controversially required operators to share infrastructure at cost (RURA, 2011). Both Operator A and the government voiced concern that mandating infrastructure sharing could chill future investment. However, the ex post sharing mandate allowed new operators to expand their networks much more quickly. Because the ex post policy change left the regulator with a bad aftertaste, the government used a new model as the next round of infrastructure was rolled out: it granted a South Korean firm a license to build a single, wholesale 4G network, which was leased out to the operators.

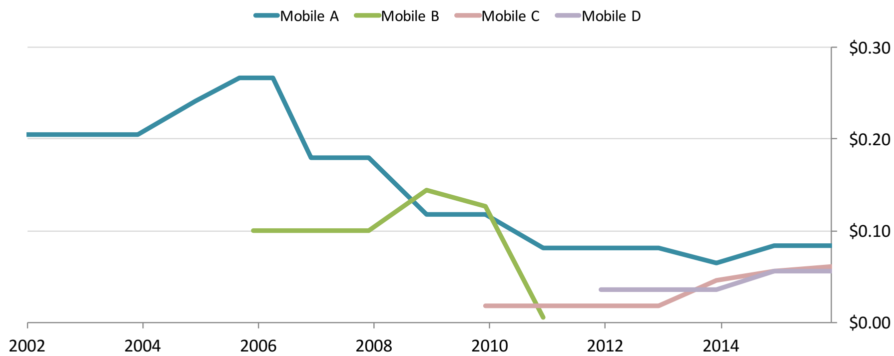
In 2011 a license was granted to a fourth operator (Operator D, replacing Operator B), which purchased the assets of the second operator. In 2011, the regulator again hired a consultant to advise on interconnection rates, who gathered detailed cost data from operators and based on a model of the cost structure, recommended lowering interconnection rates along a glide path (see Argent and Pogorelsky, 2011; RURA, 2009). See Figure 2b for the evolution of the interconnection rate and off-network prices. Figure 2c shows the coverage provided by each network; despite being able to build on the incumbent's towers, the entrants have not rolled out as complete networks. Figure 2d shows the number of accounts on each network.

Consumer Choice. The ability of competition to discipline firms depends on how consumers choose between products. Table 2 shows the results of a Research ICT Africa survey of phone owners in several Sub-Saharan African countries. Consumers report selecting operators mostly based on coverage (51.4% of respondents, multiple responses allowed), which network their contacts are on (37.4%), the range of services offered (27.1%), and price (20.2%). While in markets like the U.S. operators subsidized handset purchase as part of a contract, in Sub-Saharan Africa most accounts are prepaid, and only 3.4% of respondents received a phone with a contract. Thus I will consider the handset market as separate from the market for phone plans.

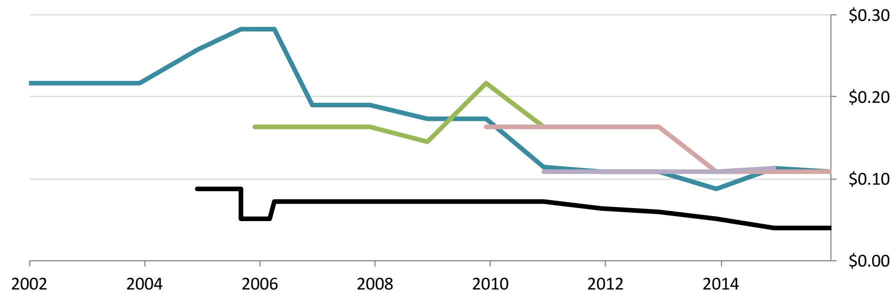
I develop a model to capture the key differentiators (coverage, price, and pricing network effects). In my model operators will not differentiate on services as there was little scope for this in Rwanda at the time.

FIGURE 2. Development of Competition in Rwanda

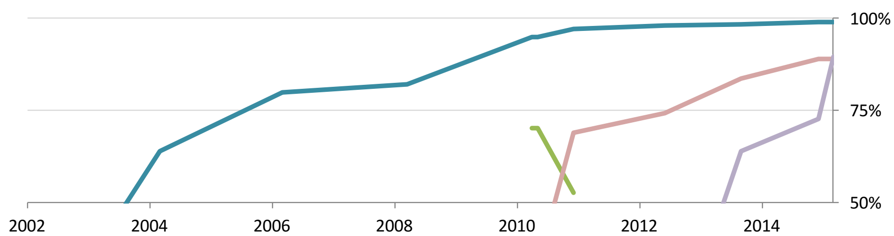
(a) Price, On Network (30 second peak call)



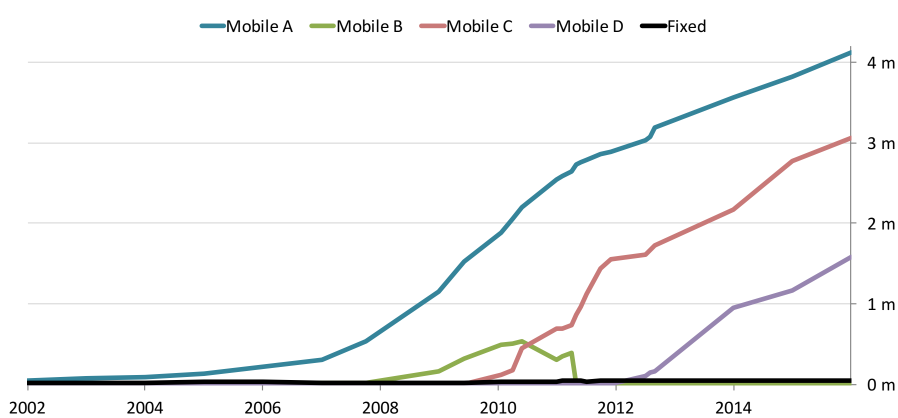
(b) Price, Off Network (30 second peak call. Black: Interconnection Rate per call)



(c) Coverage (Geographic)



(d) Accounts



In 2004 the incumbent raised the marginal price of a call while lowering a monthly subscription fee. The subscription fee was abolished in 2005. When the market was essentially a monopoly the number of accounts corresponded closely to the number of individuals with phones. Under competition, some individuals held accounts with multiple operators so that there are more accounts than phone owners (in a 2010-2011 survey, 36.9% of individuals with phones have multiple accounts (RIA, 2012)). Sources: archived operator websites and regulator reports. In response to an interconnection dispute in 2006, the regulator temporarily reduced the interconnection rate to $0.05 per call.

TABLE 2. Mobile Phone Usage in Sub-Saharan Africa

Phone owners in sub-Saharan Africa*:	2007-2008
Have two or more accounts	16.1%
Bought phone	78.1%
Received phone from friend or family	18.5%
Received phone with a contract	3.4%
Reasons you chose your current operator	
Wider coverage	51.4%
Most of my friends and family on same network	37.4%
Range of services	27.1%
Price	20.2%
Customer service	14.8%
Better voice clarity / quality	12.0%
Company reputation	9.2%
Free handset with the connection	8.9%
No other option	4.9%
Use phone for	
Making and Receiving Phone Calls	97.9%
SMS	77.3%
Email	2.5%

Source: RIA household survey 2007/2008. *: Representative samples of Benin, Botswana, Burkina Faso, Cameroon, Ethiopia, Ghana, Cote d'Ivoire, Kenya, Mozambique, Namibia, Nigeria, Rwanda, Senegal, South Africa, Tanzania, Uganda, and Zambia.

3. DATA

This project uses several data sources (for more information see Appendix B):

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 by the operator's mobile phone subscribers, numbering approximately 300,000 in January 2005 and growing to 1.5 million in May 2009. For each transaction, the data reports: anonymous identifiers for sender and receiver, corresponding to the phone number and handset, time stamps, call duration, the incurred charge (for transactions before August 2008), and the location of the cell towers used.[6]

Operator costs: Like many telecom regulators, the Rwandan regulator requires that operators interconnect their networks, under charges 'derived from relevant costs' (RURA, 2009). Because the determination of these rates are crucial to competitive interactions in the market, the regulator collects cost data from operators and cross-checks these against regional and international benchmarks. To compute the cost of operating networks of different scales, I use long run incremental costs derived from a Rwandan study completed by international consultants (PwC, 2011).

Coverage: I create coverage maps by computing the areas within line of sight of the towers operational in each month. I use a method suggested by the operator's network engineer. Elevation maps are derived from satellite imagery recorded by NASA's Shuttle Radar Topography Mission and processed by the Consortium for Spatial Information (Jarvis et al., 2008; Farr et al., 2007).

Individual locations and coverage: I infer each subscriber's set of most used geographical locations using an algorithm analogous to triangulation, a version of Isaacman et al. (2011)'s 'important places' algorithm that I have modified to improve performance in rural areas. Around each individual's most used locations, I compute the fraction of area receiving coverage in a given month using a two-dimensional Gaussian kernel with radius 2.25 km. I then compute the coverage available to each individual during each month by averaging this fraction over the individual's locations, weighting each location by the number of days calls were placed from that location.

Handset prices: I create a monthly handset price index $p_t^{handset}$ based on 160 popular models in Rwanda, weighting each model by the quantity activated on the network. I account for the introduction of new handsets by filling in missing prices with prices from handsets of comparable quality.

[6]Some months of data are missing; from the call records: May 2005, February 2009, and part of March 2009, and from the billing records: October 2006 and the months following August 2008. The records of some tower identifiers are missing from this data. I infer the location of missing towers based on call handoffs with known towers using a procedure I have developed (Bjorkegren, 2014).

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.

4. Model

In this section I describe a model of handset adoption, adapted from Bjorkegren (2017) to allow for competition. The utility of owning a phone is derived from making calls, so I begin with a model of usage. The model of usage will also account for changes that improve communication across links, specifically the expansion of coverage and reduction of calling prices.

Consumers. Let G be the communication graph (a directed social network). The nodes of the graph, N, represent individuals who eventually adopt phones. At each period, each individual $i \in N$ may have a phone or not; let $S_t \subseteq N$ be the set of individuals with phones in month t. Individual i selects a firm $a_{it} \in \{0,1\}$ to obtain service from. Different firms may offer different prices and coverage, but their networks are interoperable, so individuals can call across networks. A directed link $ij \in G$ indicates that i has a potential desire to call j over the phone network; I assume this link exists if i has ever called j. I assume these links are fixed over time. As shorthand let $G_i = \{j\,|ij \in G\}$ be i's set of contacts.

Calling Decision. At each period t where he has a phone, individual i can call any contact j that currently subscribes, regardless of the firm they subscribe to, $j \in G_i \cap S_t$, to receive utility u_{ijt}. Each month, i draws a communication shock ϵ_{ijt} representing a desire to call contact j; this desire might be high after an important event or to coordinate a meeting, or low if there is little information to share. The shock is drawn from a link-specific distribution, $\epsilon_{ijt} \overset{iid}{\sim} F_{ij}$ that will be specified later. Given the shock, i chooses a total duration $d_{ijt} \geq 0$ for that month, earning utility:

$$u_{ijt} = \max_{d \geq 0} v_{ij}(d, \epsilon_{ijt}) - c_{ijt}d \tag{4.1}$$

where $v(d, \epsilon)$ represents the benefit of making calls of total duration of d given communication shock ϵ, and c_{ijt} represents the per-second cost.

I model the benefit of making calls as:

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

where the first term represents a linear benefit and the second introduces decreasing marginal returns. $\gamma > 1$ controls how quickly marginal returns decline. α is a cost-dependent censoring parameter that controls the intercept of marginal utility, and thus affects the fraction of months for which no call is placed.

Subscribers' choice of firm affects the marginal cost of placing a call, which includes the per second price as well as a hassle cost of obtaining coverage:

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

where β_{call} represents call price sensitivity, $p_t^{a_{it}a_{jt}}$ is the per-second calling price (including any tax) for a call from firm a_{it} to a_{jt}, and $\beta_{coverage}\phi_{it}^{a_{it}}\phi_{jt}^{a_{jt}}$ represents the hassle cost when the caller or receiver have imperfect coverage. An individual's coverage $\phi_{it}^{a} \in [0,1]$ under firm a is derived from the fraction of the area surrounding his most used locations receiving cellular coverage in month t.

Given this functional form, calling prices, and coverage of both sender and receiver affect both the frequency and duration of calls. The marginal 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. This implies an optimal duration of:

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

which is larger when the desire to communicate that month (ϵ) is larger. If the desire to communicate is not strong enough, the individual would prefer not placing a call across that link: $d_{ijt} = 0$ when $\epsilon_{ijt} \leq \underline{\epsilon}_{ijt} := \frac{\alpha}{1-\beta_{price}p_t^{a_{it}a_{jt}} - \beta_{coverage}\phi_{it}^{a_{it}}\phi_{jt}^{a_{jt}}}$.

Then, the expected utility i receives from being able to call j in period t is:

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

where $\mathbf{p}_t$ represents the vector of prices for calls within and between different firms, $\boldsymbol{\phi}_t$ represents the vector of coverage for all individuals and firms, and $\mathbf{a}$ represents the firm choices for each individual (a vector of vectors).

Altogether, each month i is on network a_{it}, he receives expected utility:

$$E_\epsilon u_{it}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}, \boldsymbol{x}_{G_i}) = \sum_{j \in G_i \text{ and } x_j \leq t} [E_\epsilon u_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) + w \cdot E_\epsilon u_{ji}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a})] - S \cdot 1_{\{a_{it} \neq a_{it-1}\}} + \eta_i^{a_{it}}(1-\delta)$$

where x_j represents j's adoption time. The utility has three components. It includes expected utility from calls with contacts: u_{ij} represents the utility of calls from i to j (which i pays for), u_{ji} represents calls from j to i (which j pays for), $w \in [0,1]$ specifies how much recipients value incoming calls. If i selected a different operator for period t, he will incur the switching cost S, which includes the cost of changing accounts (swapping SIM cards and adjusting any settings), and notifying contacts about the change in phone number. Finally, it includes heterogeneity in the utility of using a phone with each operator that is unobserved to the econometrician, in the monthly flow arising from an individual's type (η_i^0, η_i^1). I do not restrict the distribution of η_i^a (specifically, it need not be mean zero), but do require that each individual's type is constant over time to make simulation tractable. Each month that i is not on the network he receives utility zero.

Adoption Decision. Conditional on the adoption decisions of others, an individual's adoption decision is an optimal stopping problem. At period t, i knows the current price of a handset, $p_t^{handset}$ (including any tax). He believes that in period $x > t$, the handset price will be exactly $E_t p_x^{handset}$, call price $E_t p_x$, and coverage $E_t \boldsymbol{\phi}_x$. (Beliefs are assumed to be point masses completely described by their expectation.) He believes that his contacts will adopt at times $E_t \boldsymbol{x}_{G_i}$ on firms $E_t \boldsymbol{a}_{G_i}$, and expects the utility of adopting at time x with operator sequence $\boldsymbol{a}$ to be:

(4.2)
$$E_t U_i^{\boldsymbol{a},x}(E_t \boldsymbol{a}_{G_i}, E_t \boldsymbol{x}_{G_i}) = \delta^x \left[\sum_{s \geq x}^{\infty} \delta^{s-x} E_\epsilon u_{is}(E_t p_s, E_t \boldsymbol{\phi}_s, \{E_t \boldsymbol{a}_{G_i}, \boldsymbol{a}\}, E_t \boldsymbol{x}_{G_i}) - \beta_{price} E_t p_x^{handset} \right]$$

i adopts at the first month x_i where he expects adopting immediately to be more attractive than waiting, given his belief about when his contacts will adopt:

$$\min_{x_i} s.t. \left[U_i^{\boldsymbol{a},x_i}(E_{x_i} \boldsymbol{a}_{G_i}, E_{x_i} \boldsymbol{x}_{G_i}) \geq \max_{s > x_i} E_{x_i} U_i^{\boldsymbol{a},s}(E_{x_i} \boldsymbol{a}_{G_i}, E_{x_i} \boldsymbol{x}_{G_i}) \right] \tag{4.3}$$

Firms. Each firm F selects a path of prices $\mathbf{p}^F$ and a tower building plan $\mathbf{z}^F$ to maximize net present profits.

Firms earn revenue from the calls of their subscribers and from interconnection fees charged to the competitor's subscribers who call in to the network. The government regulates the interconnection fee so that if i subscribes to F and calls j who subscribes to F', for each second of the call firm F pays F' amount f_{ij}.

Given a usage tax rate of $\tau_{usage,it}$, the firm revenue is given by:

$$R_F(\mathbf{p}, \boldsymbol{z}, \mathbf{a}, \mathbf{x}, \boldsymbol{f}) =$$

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

where $\boldsymbol{\phi}_t(\mathbf{z})$ is the coverage provided at time t under the rollout plans $\mathbf{z} = \{\mathbf{z}^0, \mathbf{z}^1\}$, computed using line of sight based on elevation maps.

Firms balance these revenues against the cost of building towers and operating the network. For a tower rollout plan building tower z at time x_z, the associated cost is given by:

$$C_F(\mathbf{p}, \boldsymbol{z}, \mathbf{a}, \mathbf{x}) = \sum_{z \in \mathbf{z}^F, z \text{ is off grid}} \sum_{t \geq x_z} \delta^t \left[K_{rural} \right] + B^F(\mathbf{p}, \boldsymbol{z}, \mathbf{a}, \mathbf{x}) \tag{4.4}$$

for cost of operations B^F, plus annualized cost of owning and operating rural towers K_{rural}. I compute the annualized cost of the towers using financial data provided by operators to the regulator (RURA, 2011).[7] The total annualized cost of owning and operating a tower in Rwanda is \$51,000 per year, plus \$29,584 for towers that are far from the electric grid that must be powered by generators. Other costs that the firm faces are summarized by B^F, which may include fixed costs as well as costs that vary with the amount of usage (such as switching equipment, staff, and central operations). I approximate these costs with the linear function:

[7]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.

$$B^F(\mathbf{p},\boldsymbol{z},\mathbf{a},\mathbf{x}) = fc^F + ic^F\cdot\sum_{i\in S}\sum_{t\geq x_i}\delta^t\sum_{j\in G_i\cap S_t} Ed_{ij}(\mathbf{p}_t,\boldsymbol{\phi}_t(\mathbf{z}),\mathbf{a})\cdot(1_{\{a_{it}=F\}}+1_{\{a_{jt}=F\}})$$

where fc^Frepresents the fixed cost of operating F's network, and ic^F represents the incremental cost of operating a network that sends or receives an additional second. When comparing outcomes with the same number of telecoms, the fixed cost fc^F will cancel out, so I do not attempt to estimate it. I determine ic^F from a detailed engineering study of operator costs commissioned by the regulator to set interconnection rates (see PwC 2011, and Appendix B.1).

Firms weigh revenues against the cost of tower construction to earn profits:

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

Government. The government decides whether to grant a license to the entrant firm, and if so, sets the interconnection policy f_{ij}. The government earns revenue from taxes on adoption ($\tau_{adoption,it}$) and usage ($\tau_{usage,it}$):

$$R_G = \sum_{i\in S}\left[\delta^{x_i}\tau_{adoption,it}p^h_{x_i} + \sum_{t\geq x_i}\delta^t\tau_{usage,it}\sum_{j\in G_i\cap S_t} p_t^{a_{it}a_{jt}}\cdot Ed_{ij}(\mathbf{p}_t,\boldsymbol{\phi}_t(\mathbf{z}),\mathbf{a})\right]$$

While I define aggregate profits, government revenue, and consumer utility, I take an agnostic view of the objective function that the government maximizes.

Equilibrium. The model of individual decisions presented thus far, and the estimation procedure described in the next section, are compatible with many definitions of equilibrium. However, counterfactual simulations will require a specific, tractable definition of equilibrium. There are likely to be multiple equilibria, which I will consider in estimation and simulation.

Initial adopters (S_0) are held fixed. Each other individual i decides on an adoption time $x_i\in\left[1,...,\bar{T}\right]$ and sequence of operators $a_i\in[0,1]^{\bar{T}-x_i}$ to maximize his payoff $U_i^{\mathbf{a}_i,x_i}(\mathbf{a}_{G_i},\boldsymbol{x}_{G_i})$, which depends on his contacts' adoption decisions ($\mathbf{a}_{G_i}$, $\boldsymbol{x}_{G_i}$). The number of potential states of the network is large ($2\cdot 2^{|S\setminus S_0|}>2\cdot 2^{1,000,000}$); I maintain tractability with a simplified concept of equilibrium:

First, I simplify individuals' expectations about the future. I avoid populating and managing a vast tree of potential states of the world by assuming that in equilibrium, individuals compute payoffs based on a correct anticipation of their contacts' adoption dates ($E_t\boldsymbol{x}_{G_i} = \boldsymbol{x}_{G_i}$) and operator choices ($E_t\mathbf{a}_{G_i} = \mathbf{a}_{G_i}$), with any forecast error fully captured in the constant term η_i.

Second, I simplify the strategies individuals can employ: individuals choose only two actions, their adoption time x_i and operator sequence $\mathbf{a}_i$. They may not condition their strategy on the actions of others in prior periods. This will result in a form of naiveté: individuals do not anticipate how the rest of the network will respond to their actions. Additionally, to simplify computation I allow consumers to switch operators no more than one time.

Third, I simplify firm strategies. As a condition for receiving a license, regulators commonly require firms to submit rollout plan and regular updates on prices. In Rwanda, licenses are provided conditional on approval of 5 year rollout plans.[8] To make simulation tractable, I require firms to commit to a rollout plan, as well as a path of prices, at the beginning of the license period.

An equilibrium corresponds with a Nash equilibrium of the following game. At the beginning of time, the interconnection terms $\boldsymbol{f}$ are set, either by the incumbent (unregulated interconnection) or the government (regulated interconnection). Then, each firm simultaneously announces their price sequence $\mathbf{p}^F$ and tower construction plan $\mathbf{z}^F$, and, given these plans, each individual simultaneously announces their adoption date x_i and operator sequence $\mathbf{a}_i$ (a complete information static game).

More formally, for a given vector of consumer types $\boldsymbol{\eta}$ and interconnection terms $\boldsymbol{f}$, an equilibrium $\boldsymbol{\Gamma}(\boldsymbol{\eta})$ is represented by a tuple $(\mathbf{p}^0, \mathbf{p}^1, \mathbf{z}^0, \mathbf{z}^1, \mathbf{a}, \mathbf{x})$ such that:

- For each consumer $i \in S$, adoption date x_i and operator $\mathbf{a}_i$ maximize utility $U_i^{\mathbf{a}_i, x_i}(\mathbf{p}, \boldsymbol{\phi}(\mathbf{z}), \mathbf{x}_{-i}, \mathbf{a}_{-i})$ given prices, coverage, and expectations about others' adoption dates and operator choices
- Each firm F's price sequence $\boldsymbol{p}^F$ and tower construction plan $\mathbf{z}^F$ maximize profits $\pi_F(\mathbf{p}, \boldsymbol{z}, \mathbf{a}, \mathbf{x}, \boldsymbol{f})$, given the competing firm's price sequence and tower construction plan, interconnection terms, and individual adoption dates and operator choices

[8] These appear to be enforced: in 2007 the second operator (Mobile B) was disciplined for failing to comply with its coverage and rollout plan. See Figure 5 for an example, the summary of the 2008 rollout plan.

Despite the simplicity of this definition, it will allow for rich behavior. In simulations, 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. There are also likely to be multiple equilibria.

5. Estimation and Simulation

Estimation.

Monopoly Parameters. Monopoly model primitives are estimated in Bjorkegren (2017). Individuals choose when to adopt a mobile phone and, if they adopt, how to use the phone. The usage decision reveals the value of each connection (the parameters describing the utility function: γ, α, β_{cost}, $\beta_{coverage}$, and parameters that define each shock distribution in the communication graph, $\epsilon_{ijt} \stackrel{iid}{\sim} F(\sigma_i, q_i, \mu_{ij})$). 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. By inferring the network value from the usage decision across links rather than from correlations in adoption, I overcome traditional identification issues (Manski, 1993). The adoption decision bounds any residual factors affecting adoption (bounding each individual's type under the incumbent $[\underline{\eta}_i^0, \bar{\eta}_i^0]$).

Additional Competitive Market Parameters. To estimate parameters of a competitive market not revealed in the monopoly market, I use data from a mobile operator choice survey I conducted in Rwanda in 2017. Participants were asked about their mobile phone adoption and usage, as well as hypothetical questions designed to isolate parameters describing how consumers would select between operators in the counterfactuals I study (see Appendix B.2).

Consumers describe price and service quality as primary drivers of their choices. A hypothetical choice exercise implies a very slight amount of idiosyncratic preference between the operators: I estimate that, consumers prefer the incumbent by mean $m(\eta_i^0 - \eta_i^1) = \$2.45$, and standard deviation $\sigma(\eta_i^1 - \eta_i^0) = \$6.72$. For each individual I then draw a type for the entrant $[\underline{\eta}_i^1, \bar{\eta}_i^1] = [\underline{\eta}_i^0 - e_{is}, \bar{\eta}_i^0 - e_{is}]$ for random shock $e_{is} \stackrel{iid}{\sim} N\left[m(\eta_i^0 - \eta_i^1), \sigma(\eta_i^1 - \eta_i^0)\right]$ drawn under random seed s.

Consumers find it a hassle to switch operators, especially when a switch entails changing phone numbers: I estimate a switching cost of $S = \$36.09$.

While choices in hypothetical scenarios do not always reveal true preferences, they have been shown to be effective predictors of behavior (Bernheim et al., 2013). To validate my approach, I ask respondents to make additional hypothetical choices in scenarios that are analogous to choices made within my data. While I do not observe switches between operators in my data, I do observe switches between plans offered by the same operator. Survey and data estimates imply plan switching costs that are similar in magnitude (see Appendix B.3).

Simulation. Conditional on prices and coverage, I simulate a consumer adoption equilibrium based on a change to the environment using the iterated best response method described in Bjorkegren (2017), which bounds the entire range of equilibria. The algorithm is described in pseudocode in Section C. In Section 8, I describe how this method is extended to find an equilibrium in firm strategies.

6. Monopoly Benchmarks

While simulating a competitive equilibrium will require additional assumptions, I can simulate monopoly benchmarks that suggest the effects of opening up the market to competition. I hypothesize that under competition, firms may compete more heavily in urban centers, lowering prices but reducing investment in rural coverage. To gauge these effects, I simulate two benchmarks: the benefits of lowering prices, and the distribution of revenue from investing in rural coverage. In both simulations I hold fixed individuals' operator choices ($a_{it} \equiv 0$).

How large are benefits to lowering prices? I first estimate the scope for competition to improve welfare by simulating if the monopolist were to charge the price that was eventually charged after the competitor entered (in 2010; see Figure 2). I simulate the monopoly immediately dropping calling prices by 77%, and holding nominal prices steady over the time period, while holding fixed all other aspects of the market. Results are shown in Table 3. The price reduction lowered firm and government revenues, and due to the costs of operating a larger network, substantially reduced firm profits. However, for net welfare these declines are far outweighed by the huge

Table 3. Benchmark Simulation: If Monopolist Reduced Price to Eventual Competitive Price

	Firm		Government	Consumer
	Revenue	Profit	Revenue	Utility
Baseline	[165, 187]	[102, 118]	[65, 73]	[244, 270]
Lowered prices	[145, 156]	[34, 38]	[63, 69]	[574, 608]
Total Impact	-20, -31	-68, -80	-2, -4	330, 338

(million $)

benefits to utility (more than doubling the surplus accruing to consumers). This suggests that there is substantial scope for welfare benefits from price reductions; however, competition may affect other margins, such as investment. Given the scope for consumer benefits, I move next to consider the incentives of a firm to invest in rural coverage.

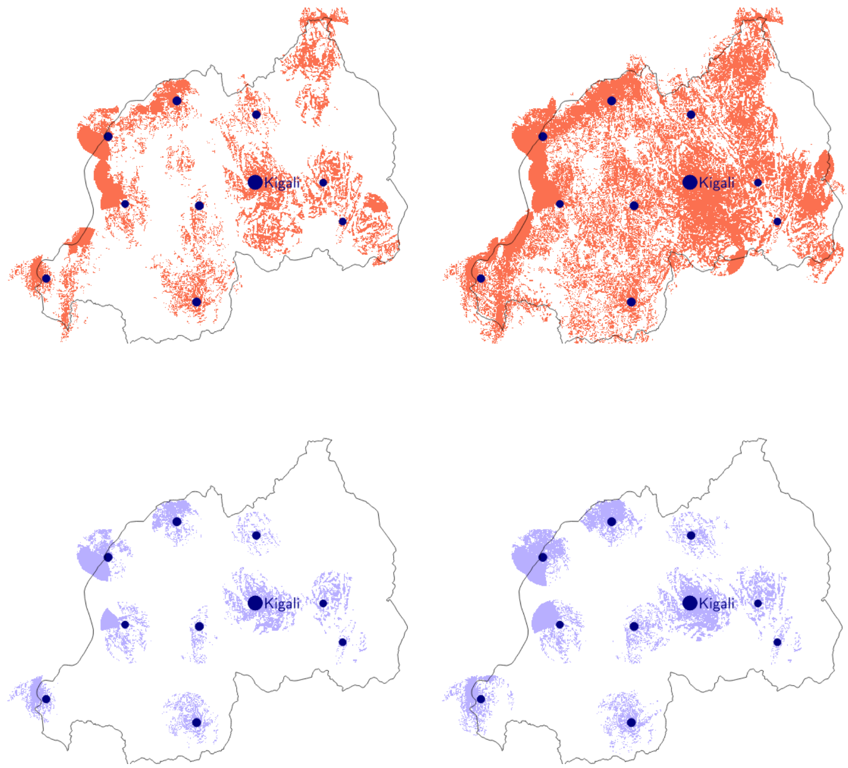
How much benefits of rural expansion comes from the urban network? I estimate the scope for an effect on investment in infrastructure by decomposing the revenue generated under monopoly provision into pieces that would be fully and only partially internalized under competition. It tends to be profitable to serve urban areas even in the presence of competition. But serving a rural area may only be profitable if one also has a monopoly over urban areas. If market share in urban areas is split between competitors, an operator may invest less in rural coverage: it will internalize less of the spillover benefits of investment, and if price discrimination is limited, price pressure in the urban area may limit its ability to recoup the cost of the rural investment.

I simulate the effects of building full baseline coverage relative to a counterfactual where only urban towers were built (see Figure 3 for coverage maps). I impose the relevant coverage map, allow each consumer to adjust their adoption and calling behavior, and compute resulting equilibrium revenues and utility. I then decompose the revenue generated by the investment, by rural-rural, urban-rural, rural-urban, and urban-urban connections. If there were competition for the urban market, revenue

Figure 3. Rollout Plans

Observed Incumbent Rollout 2005 2009

No Rural Expansion



in the last three categories would only partially be internalized.[9] If this portion represents a large fraction of the revenue impact of the coverage expansion, that suggests that competition may have a large impact on investment.

Rural expansion generated large welfare benefits, but they were dispersed among parties, as shown in Table 4. The overall annualized cost of operating the rural towers was approximately \$6.8m, but it generated \$73m in utility, \$10m in government revenue, and \$28m in firm revenue (in the low equilibrium; \$76m, \$11m, and \$32m in the high equilibrium). When a monopolist owns the network, it would internalize revenue from all links. However, if the network were split it would internalize only a

[9]An operator that builds a rural network will earn revenue on rural-rural calls, a portion of the additional calls between urban and rural networks (per interconnection rates), and a portion of urban-urban calls—depending on how much of the urban network the firm owns.

TABLE 4. Benchmark Simulation: If Monopolist Had not Built Rural Network

	Utility	**Government Revenue**	**Firm Revenue**				
				By Connection			
	All links	All links	All links	Rural-Rural	Rural-Urban	Urban-Rural	Urban-Urban
Baseline	[244, 270]	[65, 73]	[165, 187]	[30, 33]	[17, 18]	[24, 28]	[95, 108]
No expansion	[169, 189]	[56, 62]	[137, 153]	[22, 25]	[13, 15]	[18, 21]	[83, 93]
Impact	**-75, -81**	**-9, -11**	**-28, -34**	-8, -8	-4, -4	-6, -7	-12, -15
	million $						
Cost of Expansion	6.8	(annualized)					

fraction of this revenue. To gauge how revenue would be split, I break down the revenue earned by type of connection. Revenue is fairly dispersed: \$7m (\$8m in the high equilibrium) arose from rural-rural connections, \$4m from rural-urban connections, \$6m (\$5m) from urban-rural connections, and \$11m (\$14m) from urban-urban connections. While rural areas received improved coverage, a substantial portion of the revenue came from urban-urban links. This is partly because some urban consumers spend time in rural areas and thus directly benefit from coverage (which would be factored into their coverage measure ϕ_{it}^{a}), and partly due to spillover benefits to the large urban network.

These simulations suggest that the revenue from expansion would likely be split among several parties. While in this case the full expansion would would be profitable even if the monopolist only internalized the rural-rural revenue (since revenue $\$8m > \$6.8m$ cost), if it only obtained a portion of revenue it may have been more profitable to roll out less than full coverage. Also, these simulations hold prices fixed; in a competitive environment the firm may be forced to lower prices which may further reduce incentives to expand. To evaluate the impact of competition on rural expansion, including the potential for partial rollout and price changes, I use the model to simulate a competitive industry. The next section discusses assumptions needed to simulate competition, and Section 8 presents results.

7. Extension to Competition

Given that many features of the environment could change with the introduction of competition, this section evaluates how sufficiently the model estimated in an essentially monopolistic environment captures behavior under competition. The model imposes constraints on how operators would compete, and how consumers would respond. This section discusses and tests these assumptions. In particular, I require that the individual types for the incumbent η_i^0, and the latent call graph (μ_{ij}, σ_i, q_i) remain stable upon the introduction of competition, and that the call graph remains the same regardless of which operator an individual subscribes to.

To evaluate these questions I use evidence from two sources. First, a viable competitor did enter the Rwandan market after the rollout, in the end of 2009. I use evidence from the Rwandan market after this competitor's entry; from surveys, official statistics, and from an original consumer choice survey. Second, I report evidence from other African countries that had competitive markets during this time.

What margins might operators compete on? The model captures the most essential margins that operators would compete on: coverage and price levels (which may include network effects related to price and coverage). In a representative survey of individuals with phones in sub-Saharan Africa, these are among the top reasons that individuals indicate for choosing their operator (51.4% report coverage; 20.2% report price; 37.4% report because it is the network their contacts are on, which typically is due to network prices; Stork and Stork 2008, as reported in Table 2). Here I evaluate whether the incumbent would compete with an entrant on other margins.

Price Schedule. Competing operators could potentially differentiate their plans and pricing in ways not adequately summarized in price levels (for example, one operator might specialize in voice and the other in SMS). However, there is little evidence of such specialization after the introduction of competition in Rwanda.[10] The entrant's

[10]With the exception that several years later once smartphones had gained popularity, the fourth entrant in Rwanda (Operator D) specialized in data plans.

plans were very similar to the incumbent; the incumbent reduced the prices of different services in a nearly proportional manner; and different services appear to grow proportionally between the operators (see Appendix A.1).

Quality. The model includes service quality as indicated by coverage, measured by the accessibility of towers in a radius of the locations an individual uses a phone most. To the extent that the expansion of coverage corresponds with other measures of geographical quality (such as the frequency of dropped calls and the availability of airtime from agents), coverage represents a proxy, and the estimation procedure will capture how consumers respond to the combined measure of quality. Other call quality measures are regulated under the terms of each operator's license; quality tests by the regulator suggest little difference between the operators. Other aspects of quality do not appear to be major differentiators. (See Appendix A.2).

Handsets. In many developed countries, mobile phone operators differentiate themselves based on selection and pricing of handsets. However, in African markets the market for handsets has been relatively independent from the market for mobile service (in 2008 only 3.4% of phone owners in sub-Saharan Africa had received their handset with a contract, as reported in Table 5). Further, most African operators use the same GSM standard so that the same handset can be set up on any of the networks.[11] In Rwanda, while operators have stores that sell handsets, during the period of my data, operator sales records account for only 10% of total handsets activated. I assume that the entry of an operator would not change the prices or availability of handsets.

Other Services. As they spread, mobile phones began to provide additional services beyond voice, including mobile money and internet. However, most of these services either developed later than the period of study, or were not differentiated across operators (see Table 5 and Appendix A.3).

[11]One exception: the ineffective competitor (Mobile B) operated an incompatible CDMA network from 2005-2008 before switching to GSM. During this earlier period, handsets sold for use on Mobile B were not compatible with Mobile A or most other African and European networks.

Table 5. Mobile Phone Usage

	2007-8		2010-11	
	SSA	Rwanda	SSA	Rwanda
Two or more accounts	16.1%	3.1%	23.7%	36.9%
Bought new phone	66.5%	84.0%	63.0%	61.5%
Bought used phone	11.6%	10.6%	10.9%	23.3%
Got a new or used phone from friend or family	18.5%	5.1%	15.6%	12.2%
Got a phone with a contract	3.4%	0.2%	10.5%	3.0%
Use phone for				
Making and Receiving Phone Calls	97.9%	94.8%	99.4%	99.7%
SMS	77.3%	87.6%	83.5%	92.2%
Roaming when abroad	-	-	5.3%	6.7%
Sending or receiving money	-	-	18.4%	17.5%
Transferring airtime	-	-	41.9%	45.5%
Email	2.5%	1.6%	13.5%	13.3%
Browsing Internet	-	-	17.2%	14.9%
Facebook or other social network	-	-	16.0%	13.6%
Downloaded apps	-	-	15.0%	6.4%
Personal organizer / diary / watch	42.5%	41.7%	50.6%	47.2%
Playing games	20.2%	31.8%	47.7%	38.3%
Listen to music/radio	14.0%	6.4%	46.3%	35.0%
Taking photos or videos	15.1%	4.8%	39.3%	24.0%

Source: RIA household surveys 2007/2008 and 2010/2011. A dash indicates that question was not asked in that survey round.

8. The Effects of Competition

This section presents the results of simulations with competition.

Assumptions. I make the following simplifications:

Operators cannot charge different prices for on- and off-net calls ($p_t^{F,G} \equiv p_t^{F,G'}$)*.* If operators charge different prices for on- and off-net calls, the number of equilibria balloons, based on whether cliques of users tip into one network or the other. To limit this proliferation of equilibria, I assume that operators cannot charge different prices for on- and off-net calls.[12] This can be considered a competition rule imposed by the regulator, so that counterfactuals show the effect of introducing competition under this rule. While such a rule was not common in African markets at this time, it has been proposed for Rwanda (Argent and Pogorelsky, 2011), and has been used in several countries in an attempt to discipline competition (including Kenya, Singapore, Colombia, Turkey, Slovenia, and Portugal; see TMG (2011)).[13]

No multihoming. In markets where different operators have low on-net prices and high off-net prices, it can be common for consumers to hold accounts with multiple operators to connect with others on different networks.[14] Given that I restrict off-network pricing, there is less reason for consumers to hold multiple accounts; for simplicity I rule out that possibility.[15]

Consumers may switch operators, at most once. In the monopoly case, where consumers are choosing only when to adopt, assumptions about future utility do not affect the relative attractiveness of adopting at different times before the end period. However, when consumers can choose between multiple operators upon adopting, assumptions about future utility affect operator choice even if consumers adopt before the end period (T). For example, a consumer may select an operator that is strictly worse before period T but substantially better afterward because it provides higher total utility. Since I am most confident about results before T, I have made two decisions to restrict the impact of these continuation values. First, as detailed in the model, I allow individuals to switch operators. To ease computation, I allow individuals to switch at most once. Second, I allow operators to select from a menu

[12]If I allowed firms to charge different prices for calls within and across networks, without more structure it would be difficult to conclude much about the market: for example, if the two operators offered comparably low on-net prices and prohibitively high off-net prices, it would be difficult to determine which operator different cliques in the network would sign up for.

[13]It may become more common to restrict on- and off-net price differentials: regulators are increasingly allowing number portability so that a consumer can switch operators and keep the same phone number. When numbers can be ported, by looking at a phone number it is no longer possible to tell if a call will be billed at an on- or off-net rate.

[14]Consumers may either swap out the account on their handset using different SIM cards, or use a handset that supports multiple accounts simultaneously (e.g., a dual-SIM handset).

[15]There could still be some reason: an individual who travels between an urban center and rural areas may want to hold a low price account that only has urban coverage as well as a higher price account that has better rural coverage. The model could accommodate multihoming, but I would need estimates of the hassle costs of using multiple accounts.

of strategies that do not diverge substantially over time, so that differences between the operators remain relatively stable. When competition was eventually introduced, operators appeared to converge rather than diverge (see Figure 2).

Break ties in favor of incumbent. If the incumbent and entrant offer equal utility I assume a consumer will choose the incumbent.

Simulation Method. First, I draw consumer preferences, entrant types $[\underline{\eta}_i^1, \bar{\eta}_i^1]$, and assume these are known by firms. I present results drawn from a single random seed.

I then compute a competitive equilibrium in two nested steps. I consider a grid of potential interconnection terms, and price and rollout paths $\{(\boldsymbol{f}, \mathbf{p}^0, \mathbf{p}^1, \mathbf{z}^0, \mathbf{z}^1)\}$. For each tuple in this grid, I compute a partial equilibrium conditioned on firm choices (prices and coverage, and interconnection terms if they are unregulated). I use the network adoption simulation method of Bjorkegren (2017), extended to allow individuals to select (and potentially switch) operators (the algorithm is described in Appendix C). For each, I compute resulting consumer surplus, revenues, and profits. A Nash equilibrium of this grid in profits is a competitive equilibrium.

I initially hold fixed the incumbent's rollout plan and set the entrant's rollout plan to mimic the incumbent's rollout in urban areas but not cover rural areas (these plans correspond to the coverage maps in Figure 3).[16] I consider a grid of potential price paths, set as a multiple of the initial monopolist price path: $\mathbf{p}^F \in \{0.3, 0.4, 0.5, 0.6, 0.7, 0.81, 1\} \cdot \mathbf{p}^{monopoly}$.

Results: Unregulated Interconnection. The incumbent can dictate the terms of interconnection for most emerging network goods, such as Facebook, Uber, and many mobile money systems. I consider the results if the incumbent were able to dictate the terms of interconnection (f_{ij}).[17]

Prior to the pricing game, I allow the incumbent to select from a menu of interconnection rates: $f_{ij} \in \{\frac{2}{3}, 1, 2, 3, 4, 5\}$ RwF/sec, and then compute the resulting Nash

[16]Operator C's Annual Report in 2010 suggested an urban focus: '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 the regulator mandated it in 2011.

[17]It is computationally inexpensive to consider different terms of interconnection: conditional on final consumer prices, consumer behavior and associated network effects are fixed.

equilibrium prices and outcomes. Table 6 (a) shows a subset of the resulting game board, for the government regulated level $f_{ij} = \frac{2}{3}$ and the alternative that leads to the most profitable equilibrium for the incumbent, $f_{ij} = 4$. Since the entrant offers weakly lower coverage, in the bottom triangular portion of the matrix the vast majority of consumers only subscribe to the incumbent. The incumbent sets interconnection to 4 RwF to incur losses at the incumbent. Outcomes are shown in Table 6 (b), and do not differ substantially from the monopoly case. This mimics observed outcomes in many emerging network goods: when one player is dominant, interconnection rarely arises endogenously.

If alternately $f_{ij} = \frac{2}{3}$, the terms set by the government, then competition leads to lowered prices. If the entrant lowers prices, it can capture a substantial portion of the revenues in the urban market. The entries suggest that the incumbent would reduce prices in response.

Results: Regulated Interconnection.

Equilibrium in Prices. Under the government's interconnection terms, outcomes are shown in Table 7.

Equilibrium in Prices and Coverage. [In progress]

.

Robustness.

Network incompleteness. In my data, adoption and usage illuminate the links of the call graph. However, I observe this illumination only through May 2009. Some individuals adopted phones after this period, so I observe a subset of the call graph for Rwanda's population. Because competition may make it more attractive to join the network, the omitted, or 'dark', portion of the network could affect my results: in a counterfactual, these individuals may have adopted during the period of interest. It is not feasible to obtain the full network from the period where the Rwandan market was competitive, since the network is then split among multiple operators. Instead, I gauge the potential bias with two exercises, which exploit the variation I observe during the period of monopoly as well as a later household survey.

Table 6. Simulation: Competitive Interaction with Coverage Fixed, Incumbent Sets Terms of Interconnection

(a) **Strategic Interaction** (Profit in million \$, high adoption equilibrium)

Incumbent		Entrant: p_t	$0.81p_t$	$0.7p_t$	$0.6p_t$	$0.5p_t$	$0.4p_t$	$0.3p_t$
$f_{ij} \equiv 4$	p_t	**107, -1**	101, -2	102, -15	83, -8	71, -14	70, -39	122, -109
	$0.81p_t$		**102, -1**	**130**, -34	**142**, -56	120, -56	80, -40	92, -81
	$0.7p_t$			_	126, -39	**147**, -77	120, -76	91, -74
	$0.6p_t$				78, **-1**	137, -67	**142**, -94	**126**, -105
	$0.5p_t$					56, **-0**	129, -83	154, -128
	$0.4p_t$						31, **-0**	141, -119
$f_{ij} \equiv \frac{2}{3}$	p_t	**109**, -2	72, 28	41, 45	27, **49**	18, 39	13, 19	8, -2
	$0.81p_t$		**103**, -2	**82**, 14	58, 28	36, **28**	22, 17	17, -6
	$0.7p_t$			_	78, 9	54, **23**	33, 10	21, -4
	$0.6p_t$				**80**, -2	**64, 6**	45, 3	29, -8
	$0.5p_t$					58, -2	**48, -2**	**36**, -11
	$0.4p_t$						32, **-2**	31, -10

Best responses denoted in **bold**; Nash equilibria underlined.

(b) **Equilibrium when incumbent dictates terms of interconnection** ($f_{ij} \equiv 4$)

Outcomes	Incumbent Firm Revenue	Incumbent Firm Profit	Entrant Firm Revenue	Entrant Firm Profit	Government Revenue	Consumer Utility
Baseline: Monopoly	[165, 181]	[102, 114]	[0, 0]	[0, 0]	[65, 71]	[244, 263]
Duopoly	[_, 175]	[_, 107]	[_, 2]	[_, -1]	[_, 70]	[_, 265]
Impact of Competition	_, -6	_, -7	_, +2	_, -1	_, -1	_, +2

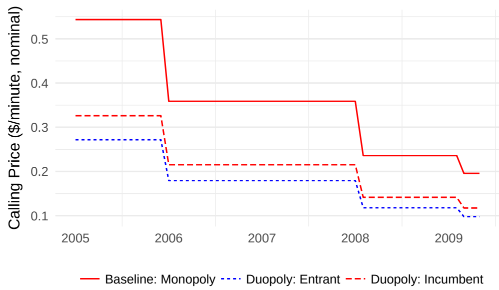
_ denotes computation still in progress.

First, I consider whether the competitive equilibrium calling price is exactly contained within the variation I observe. I can still simulate the market for the earlier period of the network, say 2005-2007, as long as adoption does not become more attractive in those years under competition than it was under the monopoly in 2009.

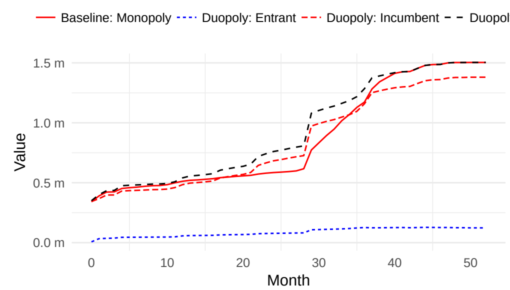
Second, I exploit more of the variation based on the tradeoff between handset prices and calling prices. In counterfactuals handset prices continue to follow the same global trend. Even if the counterfactual calling price were far lower than the monopoly range,

TABLE 7. Simulation: Competitive Equilibrium under Regulated Interconnection (Coverage Fixed)

Prices



Subscribers



Incumbent Market Share (high adoption equilibrium), May 2009	
Overall	0.94
...Urban	0.88
...Rural	0.99
...Initial Adopters	1.00
...Later Adopters	0.91

Outcomes	Incumbent Firm		Entrant Firm		Government	Consumer
	Revenue	Profit	Revenue	Profit	Revenue	Utility
Baseline: Monopoly	[165, 181]	[102, 114]	[0, 0]	[0, 0]	[65, 71]	[244, 263]
Duopoly	[_, 146]	[_, 64]	[_, 24]	[_, 6]	[_, 70]	[_, 451]
Impact of Competition	_, -35	_, -50	_, +24	_, +6	_, -1	_, +188

_ denotes computation still in progress.

an individual may still choose to delay adoption if handset prices remain high. I bound the behavior of this ‘dark’ part of the network by obtaining basic data on individuals subscribing between 2009 and 2011 from a nationally representative household survey, and bounding their counterfactual decisions using my model (RIA, 2012). For details see Appendix D. Results suggest that handset prices continue to be a major barrier to adoption of the dark part of the network for the range of competitive usage prices suggested by my simulations.[18]

.

[18]Note that this exercise is partial equilibrium in the sense that it holds fixed firm actions: in full equilibrium, operators may charge lower prices when facing the potential adoption of the dark part of the network.

9. Conclusion

Societies are deciding how to discipline the increasing number of industries characterized by network effects. Developing societies face a particular challenge: mobile phone networks provide the infrastructure (the 'rails') for an increasing array of vital services, including payments and banking. This paper evaluates the scope for competition to affect welfare and investment in the Rwandan mobile phone network during a period of high growth.

References

Argent, J. and N. Pogorelsky (2011): "Enhancing Performance in Telecommunications to Improve Rwandan Competitiveness," .

Armstrong, M. (1998): "Network Interconnection in Telecommunications," *The Economic Journal*, 108, 545–564.

Bernheim, B. D., D. Bjorkegren, J. Naecker, and A. Rangel (2013): "Non-Choice Evaluations Predict Behavioral Responses to Changes in Economic Conditions," Working Paper 19269, National Bureau of Economic Research.

Birke, D. and G. P. Swann (2010): "Network effects, network structure and consumer interaction in mobile telecommunications in Europe and Asia," *Journal of Economic Behavior & Organization*, 76, 153–167.

Bjorkegren, D. (2012): "Learning about Mobile Phones," Working Paper.

——— (2014): "Inferring Missing Cell Tower Locations using Call Handoffs," *White Paper*.

——— (2017): "The Adoption of Network Goods: Evidence from the Spread of Mobile Phones in Rwanda," .

Blumenstock, J. E., N. Eagle, and M. Fafchamps (2016): "Airtime transfers and mobile communications: Evidence in the aftermath of natural disasters," *Journal of Development Economics*, 120, 157–181.

Faccio, M. and L. Zingales (2017): "Political Determinants of Competition in the Mobile Telecommunication Industry," Working Paper 23041, National Bureau of Economic Research, dOI: 10.3386/w23041.

Fainmesser, I. P. and A. Galeotti (2015): "Pricing Network Effects," .

——— (2016): "Pricing Network Effects: Competition," SSRN Scholarly Paper ID 2874886, Social Science Research Network, Rochester, NY.

Farr, T. G., P. A. Rosen, E. Caro, R. Crippen, R. Duren, S. Hensley, M. Kobrick, M. Paller, E. Rodriguez, L. Roth, D. Seal, S. Shaffer, J. Shimada, J. Umland, M. Werner, M. Oskin, D. Burbank, and D. Alsdorf (2007): "The Shuttle Radar Topography Mission," *Reviews of Geophysics*, 45.

Farrell, J. and G. Saloner (1985): "Standardization, Compatibility, and Innovation," *The RAND Journal of Economics*, 16, 70–83.

Goolsbee, A. and P. J. Klenow (2002): "Evidence on Learning and Network Externalities in the Diffusion of Home Computers," *Journal of Law and Economics*, 45, 317–343.

Isaacman, S., R. Becker, R. Caceres, S. Kobourov, M. Martonosi, J. Rowland, and A. Varshavsky (2011): "Identifying Important Places in People's Lives from Cellular Network Data," in *Pervasive Computing*, ed. by K. Lyons, J. Hightower, and E. Huang, Springer, vol. 6696 of *Lecture Notes in Computer Science*, 133–151.

Jarvis, A., H. Reuter, A. Nelson, and E. Guevara (2008): "Hole-filled seamless SRTM data V4," *CIAT*.

Katz, M. L. and C. Shapiro (1985): "Network Externalities, Competition, and Compatibility," *The American Economic Review*, 75, 424–440.

Laffont, J.-J., P. Rey, and J. Tirole (1998): "Network Competition: I. Overview and Nondiscriminatory Pricing," *The RAND Journal of Economics*, 29, 1–37.

Laffont, J.-J. and J. Tirole (2001): *Competition in Telecommunications*, MIT Press, google-Books-ID: ucS5F4lg6TkC.

Mann, L. and E. Nzayisenga (2015): "Sellers on the street: the human infrastructure of the mobile phone network in Kigali, Rwanda," *Critical African Studies*, 7, 26–46.

Manski, C. F. (1993): "Identification of Endogenous Social Effects: The Reflection Problem," *The Review of Economic Studies*, 60, 531–542.

Mas, I. and D. Radcliffe (2011): "Scaling Mobile Money," Tech. rep., Bill and Melinda Gates Foundation.

Moody's (2015): "Africa's maturing telecoms sector to see further M&A activity," Https://www.moodys.com/research/Moodys-Africas-maturing-telecoms-sector-to-see-further-MA-activity–PR_325275.

PwC (2011): "Rwanda Interconnection Costing Model," .

RIA (2012): "Household Survey," *Research ICT Africa*.

Rohlfs, J. (1974): "A Theory of Interdependent Demand for a Communications Service," *The Bell Journal of Economics and Management Science*, 5, 16–37.

RURA (2005): "Annual Report," .

——— (2006): "Annual Report," .

——— (2009): "Interconnection Guidelines," .

——— (2011): "Guidelines for Siting and Sharing of Telecommunication Base Station Infrastructure," *Republic of Rwanda*.

Rwanda (2008): "Official Gazette of the Republic of Rwanda," 47.

Ryan, S. P. and C. Tucker (2012): "Heterogeneity and the dynamics of technology adoption," *Quantitative Marketing and Economics*, 10, 63–109.

Saloner, G. and A. Shepard (1995): "Adoption of Technologies with Network Effects: An Empirical Examination of the Adoption of Automated Teller Machines," *The RAND Journal of Economics*, 26, 479–501.

Stork, C. and M. Stork (2008): "ICT Household Survey Methodology & Fieldwork," Tech. Rep. 1, Research ICT Africa.

TMG (2011): "On-net/Off-net Price Differentiation: Review of International Precedent," .

Tucker, C. (2008): "Identifying Formal and Informal Influence in Technology Adoption with Network Externalities," *Management Science*, 54, 2024–2038.

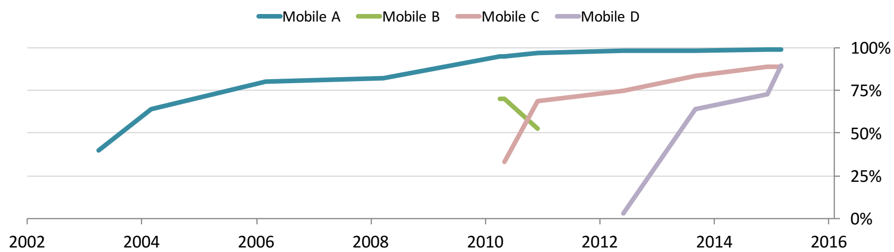
Valletti, T. M. and C. Cambini (2005): "Investments and Network Competition," *The RAND Journal of Economics*, 36, 446–467.

Vogelsang, I. (2013): "The Endgame of Telecommunications Policy? A Survey," *Jahrbuch fur Wirtschaftswissenschaften / Review of Economics*, 64, 193–269.

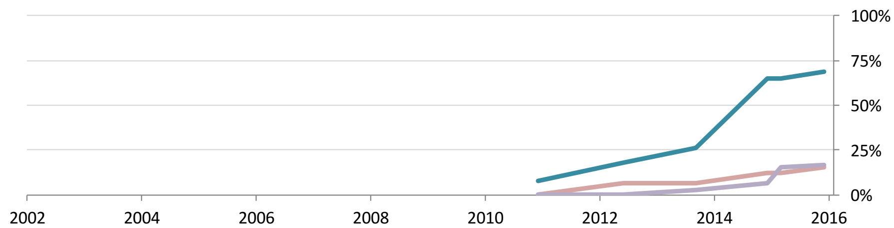
Williams, M. D. J., R. Mayer, and M. Minges (2011): *Africa's ICT Infrastructure : Building on the Mobile Revolution*, World Bank.

FIGURE 4. Coverage by Technology

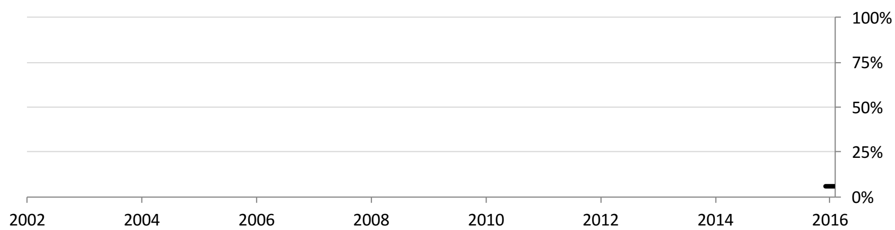
(a) 2G Network



(b) 3G Network (Mobile Internet)



(c) 4G Network (Mobile Broadband): Shared Wholesale Network



WORLD BANK (2004): *A Model for Calculating Interconnection Costs in Telecommunications*, World Bank Publications.

APPENDIX A. POTENTIAL DIFFERENCES UNDER COMPETITION

A.1. **Plan Offerings.** As one test, I evaluate how the market in Rwanda unfolded. I compare the incumbent's detailed price schedule to the entrant's schedule, Table 8. After the introduction of competition, the incumbent lowered prices to almost match the entrant, in an almost proportional way. Three years after the introduction of competition, the incumbent had a higher price level but identical SMS charges. This suggests that the firms did not target different usage profiles. Other plan characteristics (discount timebands, top up structure) were very similar between entrant and incumbent and did not change much upon the entry of the competitor. Their top up

FIGURE 5. Rollout Plan

In Rwanda, operators submit a detailed 5 year rollout plan, which must be consistent with the obligations spelled out in the license:

(a) Operator A (incumbent)

OG n°24bis of 15/12/2008

APPENDIX E: COVERAGE AND ROLL OUT

COVERAGE (URBAN AREAS AND INTERCONNECTING HIGHWAYS)

The licensee shall install, operate and maintain the Licensed Network and provide the Licensed Services in all the localities indicated below and in accordance with the target percentage coverage.

NETWORK ROLL OUT

Period	Geographic Areas & Population Percentage Coverage	Percentage Coverage						Major Roadways		Equipment/ Technologie	Capacity in terms of subscribers				
		2008	2009	2010	2011	2012					2008	2009	2010	2011	2012
2008-2012	All District Head quarter	100	100	100	100	100		Kigali-Muhanga-Ruhango-Nyanza-Huye-Nyamagabe. Kigali-Rwamagana-Kayonza-Gatsibo-Nyagatare-Kagitumba. Kigali-Musanze-Rubavu Kigali-Gicumbi-Gatuna. Rwamagana- Rusumo. Muhanga-Karongi.		GSM /UMTS	1,300,000	1,545,229	1,756,660	1,938,537	2,071,024
	All Border Points	90	100	100	100	100									
	All Sectors	85	92	100	100	100									
2012-2023	**Before the end of each five years period, the Licensee shall provide a detailed network rollout and coverage plan for the subsequent five years.**														

(b) Operator B (poorly performing entrant)

OG n°24bis of 15/12/2008

APPENDIX E: COVERAGE AND ROLL OUT

COVERAGE (URBAN AREAS AND INTERCONNECTING HIGHWAYS)

The licensee shall install, operate and maintain the Licensed Network and provide the Licensed Services in all the localities indicated below and in accordance with the CAPEX Plan presented in the Technical Offer.

NETWORK ROLL OUT

Period	Geographic Areas & Population Percentage Coverage	Coverage						Major Roadways		Equipment/ Technologie	Capacity				
		2008	2009	2010	2011	2012					2008	2009	2010	2011	2012
2008-2012	Gasabo, Nyarugenge, Kicukiro, Muhanga, Huye, Nyamagabe,Rusizi, Ruhango, Nyanza, Karongi, Rwamagana, Ngoma, Ngororero, Rubavu, Musanze, Gicumbi,	60%	70%	75%	78%	80%		Kigali-Muhanga-Ruhango-Nyanza-Huye-Nyamagabe. Kigali-Rwamagana-Kayonza-Gatsibo-Nyagatare-Kagitumba. Kigali-Musanze-Rubavu Kigali-Gicumbi-Gatuna. Rwamagana- Rusumo. Muhanga-Karongi.		GSM /UMTS	600,000	1, 000,000	1, 500,000	2, 000,000	2, 5000,000
	Rutsiro, Kirehe, Gakenke, Rulindo, Nyaruguru, Gisagara, Gatsibo, Kamonyi, Burera, Nyamasheke, Bugesera, Nyagatare, Nyabihu, Kayonza	40%	50%	60%	75%	80%									
2012-2023	.														

Before the end of each five years period, the Licensee shall provide a detailed network rollout and coverage plan for the subsequent five years.

Source: Rwanda (2008)

policies differed slightly (minimum top up of 500 RwF for the incumbent which gave 90 days of network access. The entrant offered top ups starting at 300 RwF with 30 days of access, or 1000 RwF with 60 days of network access.

As another test, Figure 6 presents the time series of prices and volumes for calls and SMS. Call and SMS prices follow similar downward trends, and volumes follow similar upward trends.[19]

A.2. **Quality.** Rwandan licenses specify that operators must maintain a dropped call rate below 2%, above 90% of connections must have good voice quality, above 95% SMS success rate, a delay between the sending and receiving of SMS of less than 48 hours, network availability above 98% for mobile switching centers, fewer than 3% of customers complaining within 30 days, and above 95% of complaints resolved within 24 hours (Rwanda, 2008). The government has sharply fined operators in the past when quality standards were not met, so these can be thought of as a lower bound on quality. Regulator tests in 2012-2013 reported little difference between the operators: a call setup success rate of 94.7% for operator A vs. 93.7% for operator C; a call drop rate of 0.5% for operator A vs. 1.5% for operator C; and an average call setup time of 6.59 seconds for operator A vs. 6.67 seconds for operator C. Only 12% of surveyed consumers in sub-Saharan Africa list voice quality among the main reasons for choosing their current operator.

Airtime sales networks do not appear to be a major source of differentiation (Mann and Nzayisenga, 2015). Other aspects of quality do not appear to be a great differentiator across sub-Saharan Africa: only 14.8% list customer service among the main reasons for choosing their current operator (see Table 2).

A.3. **Additional Services.** Mobile money and internet were uncommon at this point. Only 5 sub-Saharan African countries had mobile money systems before 2009, and the first mobile money system in Rwanda launched in 2010 (Mas and Radcliffe, 2011). Mobile internet use was also very low: only 2.5% of sub-Saharan Africans with mobile phones used them to check email in 2007-8 (the only internet usage question

[19]The third operator saw a spike in SMS volumes in late 2013; it is unclear if this spike was related to a drop in price in 2012 or some other factor.

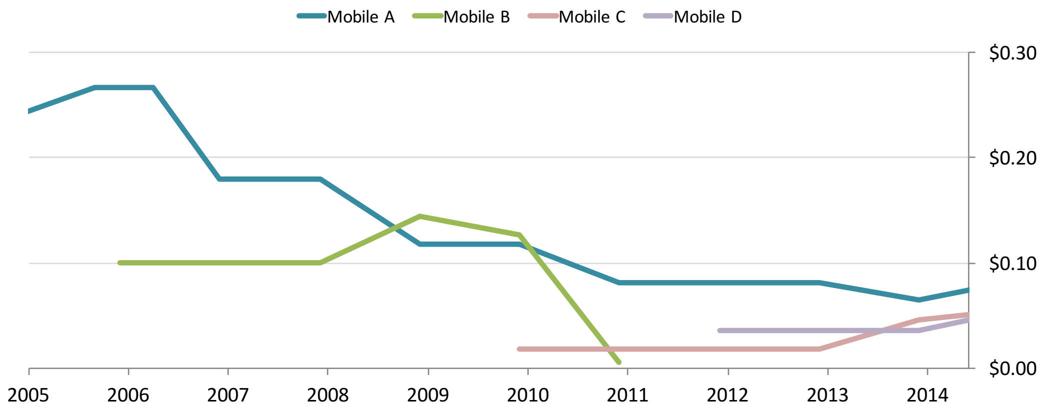
Table 8. Plan Comparison

			Essential Monopoly		Competition between A and C					
		Year	**2006 (baseline)**	**2009**	**2010**		**2013**		**2016**	
		Operator	A	A	A	C	A	C	A	C
Price	RwF, and percent of baseline per second or message									
Voice	On Net	Peak	3.3 100%	1.8 55%	1.5 45%	1.5 45%	0.75 23%	0.42 13%	0.62 19%	0.58 18%
		Off-Peak	2.8 100%	1.2 43%	1.1 39%	1 36%	0.55 20%	0.42 15%	-	-
		Happy Hour	0.9 100%	0.4 44%	0.15 17%	-	0.15 17%	-	0.02 2%	-
	Off Net	Anytime	3.5 100%	2.1 60%	2.1 60%	1.5 43%	1.5 43%	1.5 43%	0.62 18%	0.58 17%
SMS	On Net		53 100%	30 57%	30 57%	25 47%	10 19%	10 19%	12 23%	11 21%
	Off Net		53 100%	53 100%	53 100%	25 47%	25 47%	25 47%	26 49%	26 49%
Top Ups	Smallest available (RwF)		500/2500	500	500	300/1000	500	300/1000	500	300/1000
	Validity (days)		0/30+	90	90	30/60	90	30/60	90	30/60
Timebands	Peak		M-F 5-21 Sat 5-15	M-F 5-15	M-F 5-24	M-F 6-20	M-F 5-24	M-F 6-20	M-Sun 5-23.30	All times
	Happy Hour		M-Sat 1-5 Sun 0-7 Sun 23-24	M-Sat 0-5 Sun 0-7 M-Sun 23-24	M-Sun 0-5	-	M-Sun 0-5	-	M-Sun 23.30-5	-
	Off Peak		All other	All other	All other	All other	All other	All other	-	-

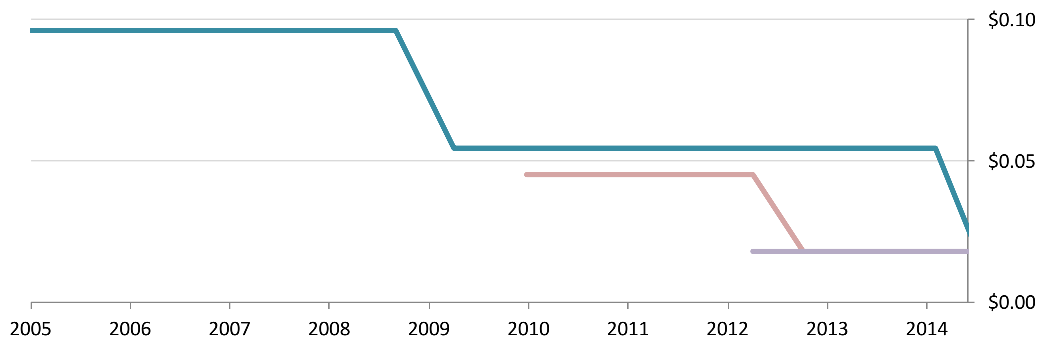
Nominal prices. Source: Archived operator websites (archive.org) and regulator reports. Incumbent also offered a load based pricing plan. Opening an account requires purchasing a SIM card; operator A charged \$1.81 for a SIM card preloaded with \$0.91 of credit; operator C charged \$0.63 for a SIM card preloaded with \$0.54 of credit.

FIGURE 6. Calls and SMS Price and Volume Series

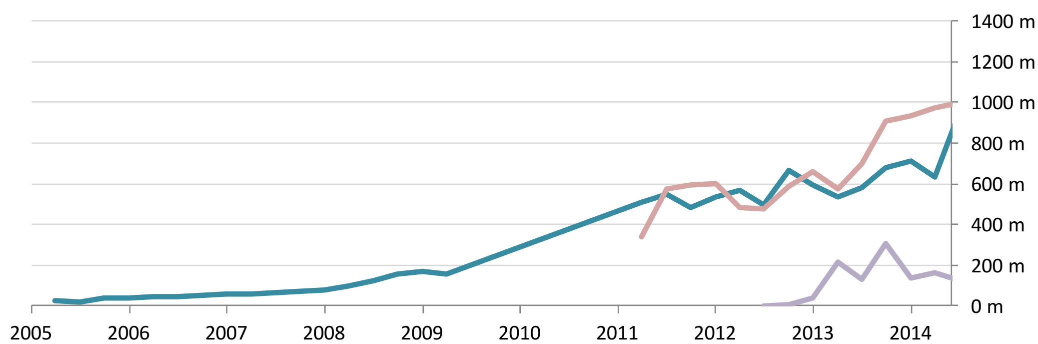
(a) Call Prices (on-network)



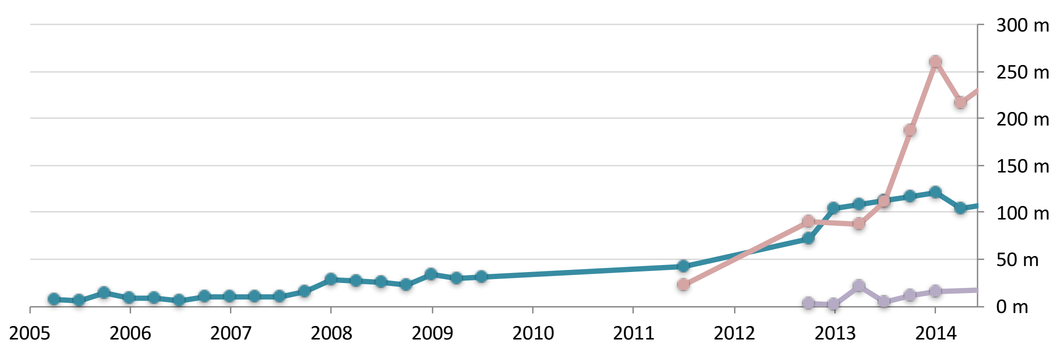
(c) SMS Prices (on-network)



(b) Call Volumes (quarterly)



(d) SMS Volumes (quarterly)



Sources: compiled together from RURA and call records. Omitted outliers from RURA data in 2011 and after 2014.

asked in that survey round). These services grew after the period of interest; in 2010-11, 18.4% used phones to transfer money, 13.5% to check email, and 17.2% to browse the internet. At present, all major operators in Rwanda offer mobile money and internet. The future introduction of these services would affect individual utilities through the discounted future stream of unobserved benefits in η_i. The development of these additional services would not affect decisions during the period of study, as long as competition does not affect how consumers anticipate the incumbent to provide these services in the future, and consumers don't anticipate the introduction of these services differentially between the two operators.

Consumers also report using mobile phones for activities other than calls, including as a personal organizer (43% of African and 42% of Rwandan phone owners), for games (20% of African and 32% of Rwandan), for music or radio (14% of African and 6% of Rwandan), and for taking photos and videos (15% of African and 5% of Rwandan). However, at this point in time, when these features were available they were built in to handsets and would not be differentiated across operators.[20]

There is a small set of services that could potentially have been differentiated across operators, such as voice mail or call waiting. The incumbent did provide a service to transfer small amounts of airtime credit which could function as a primitive form of mobile money, but it saw little use (see Blumenstock et al., 2016).[21] Many other services were available on all networks. I assume any differentiation arising from these services would have been negligible.

Appendix B. Data Details

B.1. **Cost Data.** I use the costs from an interconnection cost study commissioned by the regulator in 2010 (PwC, 2011). This study derives the incremental costs of different services from a detailed engineering model following the methodology of (World Bank, 2004).[22] From each operator, the regulator requested data on network

[20]For example, many feature phones sold in African markets have radios, and games often came standard with feature phones, such as the popular game Snake included with many Nokia phones.
[21]Mobile C introduced a feature that plays music while a caller is waiting for the receiver to pick up.
[22]The model itself is encoded as an Excel workbook with 18 worksheets and is described in an accompanying 168 page writeup.

traffic, capacity, infrastructure (include towers, switches, transmission, and central equipment such as the home location register and voicemail platform), and the current prices of each piece of infrastructure. Because of the sensitivity of this data, the study is confidential; however, I outline its method here. The regulator sought symmetric interconnection rates, so the study models a 'generic' operator by consolidating the network design and cost data; the authors average responses for most network parameters; when one operator's response deviates from international benchmarks or averaging would be unreasonable, the authors make a judgement call. For each service (such as receiving an off-net call), the model notes which pieces of infrastructure it blocks, sums up the cost for each piece of equipment (including equipment and installation costs, depreciation, land leasing costs, a markup, and the cost of capital). Because telecommunications costs are lumpy, the marginal cost of an additional second of talk time is typically zero. The study instead computes the Long Run Incremental Cost (LRIC), which averages these lumpy costs, to compute the incremental costs of constructing and operating the network for incremental usage such as an additional minute of calling. The regulator commissioned the study to set the interconnection rate (mobile termination rate) and so is primarily interested in the incremental cost of terminating a phone call from another network.

For my project, the object of interest is how operator costs change with the scale of the network. Because my counterfactuals can induce substantial change in scale, incremental costs are more empirically relevant than marginal costs. I tailor the incremental cost model to best match the empirical setup. First, many urban towers are capacity constrained, so that operators would build more towers if the network served more calls; however, many rural towers are not: they could serve more calls without substantial investment. I consider urban towers as incremental costs, and rural towers as fixed costs (see Equation 4.4). From this model I derive incremental costs for six different calls: for both rural and urban calls, the cost of an additional second of calling on-net, placed to a different network, and received from a different network.

B.2. **Consumer Choice Survey.** To determine how consumers select between mobile phone operators, I fielded a consumer survey in Rwanda in summer 2017. 89

respondents were drawn from a convenience sample of mobile phone owners, in a mix of urban and rural sectors around Kigali. Sampling was designed to capture the early adopters contained in my mobile phone data. The survey was drafted in English and given in Kinyarwanda. 63% of respondents had an account with the dominant operator by 2009, so they would appear in the initial phone data. At the time of the survey, there were three competitive operators. 97% of respondents had an account with the incumbent (Operator A), but many had multiple accounts (85% had at least two accounts).

Table 9 compares demographics between phone owners in my consumer choice survey and a nationally representative survey fielded in 2010-2011 (RIA, 2012). Because the two surveys were fielded at different times, and later than the phone data on which my study is based, the set of consumers owning phones will differ. The first column presents the raw survey results. The second set of columns compares the demographics of consumers who adopted phones by 2011 in my survey and in RIA (2012). The final set of columns compares demographics for consumers who adopted phones by 2008, the last full year of transactions I observe. My sample is of a similar age but is more highly educated (it especially has a large fraction of individuals with tertiary education), though the difference attenuates slightly as the sample is restricted to earlier adopters.

In addition to basic usage questions, the survey included questions to calibrate parameters of the model. Respondents were asked to select between two options, where had an additional monetary savings or payment. To find the point of indifference, the monetary savings was varied until the respondent switched his or her choice.

Respondents were asked three questions about switching:

> Imagine your operator had a new discount, but to get the discount you had to set up a new account (entailing replacing your SIM card and transferring any contacts stored on your SIM).

(1) If you could keep your phone number, what is the lowest total amount you would have to save to switch to the new discount? [Selected from a switching form.]

Table 9. Survey Demographics

			Comparison to Nationally Representative Survey			
Subset:	Owned phones by	**2017**	**2011**		**2008**	
		My Survey	My Survey	RIA (2012)	My Survey	RIA (2012)
Age		30.0	32.3	29.3	35.2	32.6
Male		60%	62%	57%	69%	41%
Education	Tertiary	24%	26%	4%	22%	8%
	Secondary	57%	53%	38%	53%	51%
	Primary	16%	16%	46%	20%	35%
	None	3%	4%	13%	4%	6%
Read a letter or newspaper easily		100%	100%	77%	100%	86%
N		89	73	386	49	112

(2) If you had to change to a new phone number, what is the lowest total amount you would have to save to switch to the new discount? [Selected from a switching form.]

(3) If you had to change to a new phone number and switch operators to one of the same quality, what is the lowest total amount you would have to save to switch to the new discount? [Selected from a switching form.]

The first two questions hold fixed the operator. The first question corresponds to a setting with number portability; respondents report a mean switching cost of \$3.80 (standard error \$1.37). If they must switch phone numbers as well, respondents suggested a mean switching cost of \$21.38 (standard error \$3.06). A large hassle from switching numbers is consistent with other evidence from Rwanda; in a nationally representative survey, 31% of Rwandans said they have not switched operators because they could not keep their phone number (Stork and Stork, 2008). If they must also switch operator, to one of the same quality, they report a mean switching cost of \$36.09 (standard error \$6.03). Reported switching costs vary in intuitive ways with number of contacts. The correlation between a subscriber's number of contacts and the switching cost for the first option (which would not require telling each contact

Table 10. Consumer Choice Survey

(a) Descriptives	Mean	Mean Year this Type of Handset Purchased	Has Operator A	B	C	D	Has Multiple Operators
All respondents	1.00	2007	0.97	0.00	0.85	0.31	0.85
... owns a feature phone	0.48	2006	1.00	0.00	0.77	0.14	0.79
... owns a smartphone	0.52	2013	0.93	0.00	0.93	0.48	0.91
... owns a single SIM handset	0.13	2008	0.83	0.00	0.42	0.17	0.33
... owns a dual SIM handset	0.87	2012	0.99	0.00	0.92	0.34	0.94

	Contacts on Operator A	B	C	D
All respondents	171	0	89	7
... if ego has an account with operator	177	-	100	19
... if ego does not have an account with operator	10	0	22	2

(b) Parameters	Value
S	\$21.38
mean$(\eta_i^0 - \eta_i^1)$	\$2.45
SD$(\eta_i^0 - \eta_i^1)$	\$6.72
N	89

about a new phone number) is 0.00. On the other hand, for the second option (where each contact would need to be told), the correlation is 0.27. The correlation with the last option is 0.07; the lower correlation suggests that consumers with many contacts tend to also prefer their current operator.

Respondents were next asked about idiosyncratic preferences between Operator A and C:

> Now, imagine you had to choose one of two operators from scratch (so you would not need to transfer contacts or switch phone numbers). You may choose either [Operator A], or a new plan that [Operator C] may introduce, New [Operator C], which has the exact same coverage, network, and prices as [Operator A]. (Specifically, a call to an [Operator A] number costs the same whether you are on [Operator A] or New [Operator C].)

(1) What differences would there be between New [Operator C] and [Operator A]? (open ended)
(2) If you had to choose from scratch, which would you choose?
(3) What is the least you would need to save, or highest you would pay, to choose New [Operator C] over [Operator A]? [Respondents were shown a switching form listing the two options on each row and a decreasing amount of savings, and asked when they would switch.]
(4) Why?

In response to the first question, respondents mentioned the colors and branding, their advertising, that phone numbers beginning with Operator A's prefix are considered more prestigious, and the fact that Operator A entered the market first. In response to the third, the mean preference for Operator A was \$2.45 (standard deviation \$6.72).[23] When asked to explain their decisions, 54% of consumers said they preferred the color, ads, or branding of one of the two; 24% mentioned the incumbent had more experience or a better reputation; and 12% cited customer service (including availability of agents and service centers).[24]

B.3. **Validating Survey Estimates of Switching Costs.** I do not observe switches between operators: my data does not include them, and they were insignificant in number during this period where the main operator was essentially a monopolist. Instead I estimate through my survey (details in Section B.2). However, in the call data I do observe choices that are similar in nature: the choice of plan on the incumbent. I use the decision to switch plan as a check on my switching cost estimates.

The operator originally offered a single prepaid plan, PerMin, billed by the minute.[25] In February 2006, it introduced another prepaid plan, PerSec, billed by the second. The prices were set so that a minute call under PerMin cost the same as 45 seconds under PerSec. Shorter calls were cheaper under PerSec; longer calls were cheaper

[23] I omit three respondents who reported extreme idiosyncratic preferences for one of the operators (100x the modal response of +/- 1000 RwF. 2 preferred the incumbent, one the entrant). The respondents quoted typical reasons for preferring one of the two (reputation, usage by family and friends, service), and had typical usage patterns. I believe they misunderstood the exercise.

[24] Only a handful cited feature differences: 3 cited ring back tones (introduced by Operator C but now available on both), 1 cited roaming policies, and 1 cited a loan product introduced in 2017.

[25] Calls under the 'per minute' plan were billed by the first minute, and then 30 second increments.

under PerMin. Most subscribers place short calls, so the introduction of PerSec represented a substantial price reduction for most. This paper (and Bjorkegren 2017) models the introduction of PerSec as a price reduction, abstracting away from the plan details (pricing under PerMin depends on the distribution of an individual's call lengths). The introduction of the new plan is analyzed in detail in Bjorkegren (2012).

Because the pricing schedule of PerMin depends on the distribution of call durations, I specify a pricing function $p^P(D_{ijt})$ under operator 0 plan $P \in \{M, S\}$, which depends on the distribution of call durations, D_{ijt} and a vector of shocks $\boldsymbol{\epsilon}_{ijt}$.

Then, link ij provides utility $u^P_{ijt}(D_{ijt}) = \frac{1}{\beta_{cost}}\boldsymbol{v}_{ij}(D_{ijt}, \boldsymbol{\epsilon}_{ijt}) - p^P(D_{ijt}) - \beta_{coverage}\phi^0_{it}\phi^0_{jt}D_{ijt}$ (the analogue of Equation 4.1).

The set of calls that maximize utility under plan P is then $D^{P*}_{ijt} = \arg\max_D u^P_{ijt}(D)$, with associated utility u^{P*}_{ijt}.

Then, i will switch from PerMin to PerSec in period $\tilde{t}$ if:

$$\sum_{t \geq \tilde{t}} \delta^t \sum_{j \in G_i} u^{S*}_{ijt} - u^{M*}_{ijt} \geq S^0$$

and i will remain in PerMin if:

$$\sum_{t \geq \tilde{t}} \delta^t \sum_{j \in G_i} u^{S*}_{ijt} - u^{M*}_{ijt} \leq S^0$$

Note that if in month t, i uses plan P and places calls D^P_{ijt}, the utility gained from instead using plan P' is bounded below by:

$$u^{P'*}_{ijt} - u^{P*}_{ijt} \geq p^P(D^{P*}_{ijt}) - p^{P'}(D^{P*}_{ijt})$$

because the optimal distribution of call durations may change based on the plan.

Then for switchers, it must be that:

$$\sum_t \delta^t \sum_{j \in G_i} \left[p^S(D^{S*}_{ijt}) - p^M(D^{S*}_{ijt})\right] \geq S^0$$

and for nonswitchers, it must be that:

$$\sum_t \delta^t \sum_{j \in G_i} u^{S*}_{ijt} - u^{M*}_{ijt} \leq S^0$$

or, for some $\tilde{S}^0 \geq S^0$,

$$\sum_t \delta^t \sum_{j \in G_i} \left[p^S(D^{M*}_{ijt}) - p^M(D^{M*}_{ijt})\right] \leq \tilde{S}^0$$

If the adjustment is small ($D^M_{ijt} \approx D^S_{ijt}$) then $\tilde{S}^0 \approx S^0$, and we can estimate S^0 with the objective function:

$$S^0 = \min_S \Bigg[\left| \sum_{i \text{ switcher}} \sum_t \delta^t \sum_{j \in G_i} \left[p^S(D^S_{ijt}) - p^M(D^S_{ijt})\right] - S \right| + \left| S - \sum_{i \text{ nonswitcher}} \sum_t \delta^t \sum_{j \in G_i} \left[p^S(D^M_{ijt}) - p^M(D^M_{ijt})\right] \right| \Bigg]$$

This yields an estimate of the switching cost between PerMin and PerSec of \$6.83 (bootstrapped standard error, \$0.03[26]). This estimate is similar to the survey estimate of switching to a discounted plan on the same operator (the first switching question in Section B.2), of \$3.80 (standard error \$1.37).[27]

Appendix C. Simulation Algorithm: Network Adoption Equilibrium

Require: firm price paths $\boldsymbol{p}$ and coverage paths $\boldsymbol{\phi}$
Require: candidate adoption path $\boldsymbol{x}^0$ and operators $\boldsymbol{a}^0$

$k \leftarrow 0$
repeat
  for each individual i **do**
    for proposed adoption month $t = 0$ to $\bar{T}$ **do**
      for first operator $a = 0$ to 1 **do**
        find optimal switch point $\tilde{t}$, or if not optimal to switch, $\tilde{t} \leftarrow \bar{T}$
        $\boldsymbol{a}^*_a \leftarrow [\underbrace{a \quad a \quad \cdots \quad a}_{\tilde{t} \text{ elements}} \underbrace{(1-a) \quad (1-a) \quad \cdots \quad (1-a)}_{\bar{T}-\tilde{t} \text{ elements}}]$
        solve $t^*_a \leftarrow \arg\max_s E_t U_i^{\boldsymbol{a}^*_a, s}(\boldsymbol{a}^k_{G_i}, \boldsymbol{x}^k_{G_i})$
        $u^*_a \leftarrow E_t U_i^{\boldsymbol{a}^*_a, t^*_a}(\boldsymbol{a}^k_{G_i}, \boldsymbol{x}^k_{G_i})$
      end for
      $a^* \leftarrow \arg\max_a u^*_a$
      if $t = t^*_{a^*}$ **then**
        $x_i^{k+1} \leftarrow t$
        $\boldsymbol{a}_i^{k+1} \leftarrow \boldsymbol{a}^*_{a^*}$

[26] Standard errors computed with 1,000 bootstrap draws.
[27] One difference between these scenarios is that switching from PerMin to PerSec would not require changing SIM cards, as was posed in the survey question.

        break
      end if
    end for
  end for
  $k \leftarrow k + 1$
until $\boldsymbol{x}^k = \boldsymbol{x}^{k-1}$
return consumer partial equilibrium path $\boldsymbol{x}^k$ and operators $\boldsymbol{a}^k$

For monopoly simulations, operator choices are held fixed to $a = 0$.

Appendix D. The Response of 'Dark' Portions of the Network

I observe the network illuminated by calls ($G^T \subseteq \bar{G}$), which includes individuals who adopted mobile phones by $T =$May 2009, not all individuals in Rwanda. Could counterfactual simulations be affected by omitted individuals—the 'dark' portion of the network?

This section bounds the response of this 'dark' part of network using a household survey that is representative of all mobile phone subscribers in Rwanda in $T_{survey} =$ 2011, several years after my data ends (conducted by Research ICT Africa, an NGO). The survey includes individuals both in my data (subscribing before May 2009), and in a dark portion of the network (subscribing between May 2009 and 2011). I connect this survey to my model to bound what this dark portion of the network would have done in a counterfactual during the period 2005-2009. I assume that individuals that adopted before 2011 still have phones when surveyed in 2011.

This paper considers counterfactuals that change the utility of using a phone. Using survey data, I infer how each individual traded off usage utility against the price of handsets, in the baseline environment. Without detailed network and usage information, I cannot predict exactly what each individual will do, but I can derive suggestive bounds. For simplicity, I consider individuals receiving service from a single network operator at a price level that corresponds with the competitive price.[28]

[28] The bounds from this exercise would include those from a competitive environment with one of the operators offering the same price, if consumers did not get an idiosyncratic benefit from the entrant ($SD(\eta_i^0 - \eta_i^1) = 0$ and $mean(\eta_i^0 - \eta_i^1) \geq 0$).

In particular, the largest possible impact from the dark network can be bounded with lower bounds on each i's adoption date,

$$\underline{x}_i(\mathbf{p}) \leq x_i(\mathbf{p}, \boldsymbol{\phi}(\mathbf{z}), \mathbf{x}_{-i}, \mathbf{a}_{-i}, \boldsymbol{\eta})$$

under counterfactual calling price sequence $\mathbf{p}$. I use two survey questions. How long

ago the respondent obtained their first mobile phone reveals the baseline adoption date x_i and thus the handset price paid. How much they spent on mobile phone usage in the month prior to the survey reveals the total usage. Under the assumption that all usage is domestic voice, the latter question reveals $p_{T_{survey}} \cdot d_{iT_{survey}}$.[29]

In selecting when to adopt, individuals weigh declines in handset prices against the utility of using the handset. The model implies that the unexplained benefit of using a phone can be derived from considering a K month deviation in adoption. Since x_i is monotonically decreasing in η_i, we simply need an upper bound on $\bar{\eta}_i$. Since $\bar{\eta}_i$, is monotonically decreasing in usage utility, an upper bound $\bar{\bar{\eta}}_i$ can be obtained by using a lower bound for usage utility, $\underline{\mathrm{u}}_{i,x_i-k}(p_{x_i-k})$:

$$\bar{\eta}_i \leq \bar{\bar{\eta}}_i = \frac{1}{1-\delta^K}\left[\quad p^{handset}_{x_i-K} - \delta^K E_{x_i-K} p^{handset}_{x_i} - \sum_{k=1}^{K} \delta^{K-k} E_\epsilon \underline{\mathrm{u}}_{i,x_i-k}(p_{x_i-k}) \quad \right]$$

The survey asks how many years ago the handset was purchased, not the actual month, so I consider deviations of $K = 12$ months and allow individuals to select only between adoption years.

I assume that the total usage results from calling multiple identical links with parameters equal to the median, and facing the median product of coverage. The median link has expected monthly call utility $E_\epsilon \tilde{u}_{it}(p_t, \boldsymbol{\phi}_t)$, and an expected monthly call duration of $d^{median}_{T_{survey}} = 36.1$ seconds at the time of the survey. The total duration at the time of the survey allows me to approximately infer i's number of links: $|G_i| = \frac{d_{iT_{survey}}}{d^{median}_{T_{survey}}}$.

$$E_\epsilon u_{it}(p_t, \boldsymbol{\phi}_t, \boldsymbol{x}) \approx m(p_t, \gamma_t) := \gamma_t \cdot |G_i| \cdot E_\epsilon \tilde{u}_{it}(p_t, (\phi_{it}\phi_{jt})^{median})$$

[29]Results would be similar if usage is a combination of services but prices of different services change proportionally with voice prices.

where γ_t accounts for growth in the network by scaling the number of contacts by the total number of subscribers.[30] I use this mapping to derive bounds on usage utility:

$$m(p_t, \gamma_t^{baseline}) =: \underline{\mathrm{u}}_{it} \le E_\epsilon u_{it}(p_t, \boldsymbol{\phi}_t, \boldsymbol{x}) \le \bar{u}_{it} := m(p_t, \gamma_t^{eq})$$

where adoption in a counterfactual may exceed the baseline ($\gamma_t^{eq} > \gamma_t^{baseline}$) due to lower usage prices. Then, I consider the utility of adopting at month x. Since x_i is monotonically decreasing in the usage utility and η_i, we can obtain a lower bound of x_i by using the upper bound of both quantities:

$$E_t U_i^x(E_t \boldsymbol{x}_{G_i}, \mathbf{p}) \le E_t \bar{U}_i^x(\mathbf{p}, \boldsymbol{\gamma}^{eq}) = \delta^x \left[\sum_{s \ge x}^{\infty} \delta^{s-x} m(p_s, \gamma_s^{eq}) - E_t p_x^{handset} + \bar{\bar{\eta}}_i\right]$$

Analogous to Equation 4.3, lower bound on i's adoption date is then given by:

$$\underline{\mathrm{x}}_i(\mathbf{p}, \boldsymbol{\gamma}^{eq}) = \min_{x_i} s.t. \left[\bar{U}_i^{x_i}(\mathbf{p}, \boldsymbol{\gamma}^{eq}) \ge \max_{s > x_i} E_{x_i} \bar{U}_i^s(\mathbf{p}, \boldsymbol{\gamma}^{eq})\right]$$

Then $\gamma_t^{eq} = \sum w_i \cdot 1_{\{\underline{\mathrm{x}}_i(\mathbf{p}, \boldsymbol{\gamma}^{eq}) \le t\}}$, where w_i represents the weight of each individual in the data. Since the survey measured individuals within households, it may omit business accounts. I set the weight of each sampled individual to their sampling weight times an adjustment factor.[31] I solve for equilibrium adoption by starting with an optimistic candidate adoption path ($\boldsymbol{\gamma}^0 = \max \boldsymbol{\gamma}^{baseline}$) and iterating each individual's adoption decision until the process converges to $\boldsymbol{\gamma}^{eq}$.

I consider counterfactual usage prices during the period of my data; after this period, I assume that calling prices match what ultimately happened.

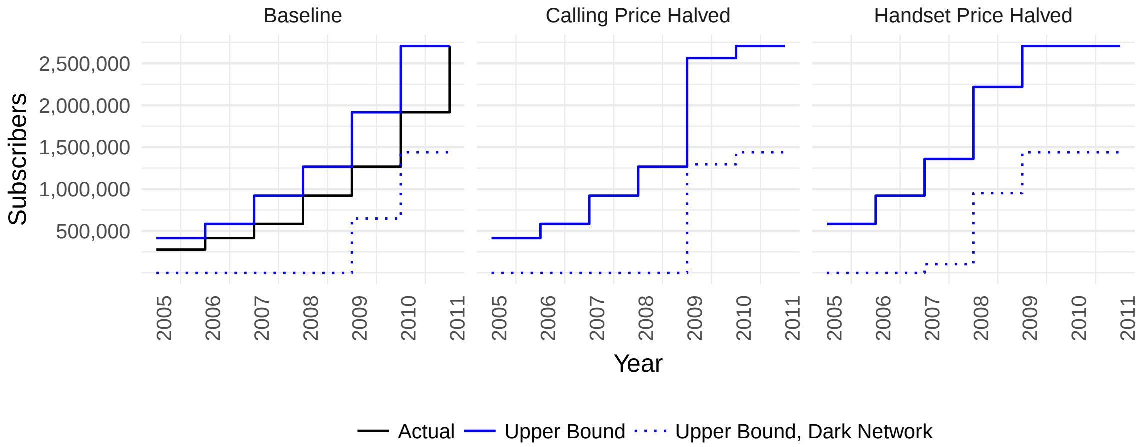
Figure 7 shows the upper bounds on adoption for all individuals and 'dark network' individuals, for the baseline and two counterfactuals that change prices from 2005-2009. The dark network's adoption is much more sensitive to handset price changes than calling prices: if the calling price were halved, the first adoptions of the dark network would be in 2009 (less than 1,294,892 nodes); if the handset price were halved, the first adoptions would be in 2007 (less than 103,722 nodes).

---

[30] $\gamma_t^{baseline}$ is derived from regulator statistics on mobile subscriptions; see Bjorkegren (2017) Supplemental Appendix.

[31] The adjustment factor is the number of accounts I observe in the data at the end of the last complete year (2008) over the total survey sample weight for individuals who report first obtaining a handset by that year.

FIGURE 7. Dark Network Bounds



The black line represents baseline adoption. The blue lines represent counterfactual adoption: the solid blue line represents total adoption, and dotted blue line represents 'dark' adoption.