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Scoping for Competition in Network Industries:
Evidence from Mobile Telecommunications in Rwanda

Daniel Bjorkegren
Brown University

SCOPING FOR: 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 is a preliminary paper that 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 identify network effects based on usage after adoption. The Rwandan government eventually allowed competition; I evaluate what may have happened had competition been introduced at an earlier stage of the network's growth. Had the monopolist simply charged the eventual competitive prices, welfare would have risen substantially. However, only a fraction of the revenue from building the rural tower network came from calls within rural areas; as a result, had the rest of the network been split among providers, there may have been lowered incentives to invest. A subsequent version of this paper will simulate the effects of competition under different policy regimes.

Preliminary and incomplete; please do not cite.

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, and operating systems: Microsoft). 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 other markets.

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. 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, because it is hard to measure network effects. First, they are often extremely dispersed. For example, 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. In order to understand the effect of an intervention into this market, one would have to measure and predict all of these ripple effects.

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 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

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[1]Early theoretical work includes Rohlfs (1974), Katz and Shapiro (1985), and Farrell and Saloner (1985). 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). The paper closest in spirit to this one is Ryan and Tucker (2012), which estimates the adoption of a videoconferencing system over a small corporate network, and evaluates policies of seeding adoption.

[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).

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.

Bjorkegren (2017) exploits these 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 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 there is an extensive theoretical literature 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 analyzes investment in countries that have changed telecom policies over time (Faccio and Zingales, 2017); however, that exercise is difficult to interpret, as firms take into account expected future policy when investing. Also, it is

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[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).

[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.

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 by using a demand model estimated under monopoly conditions to evaluate the effects of increasing competition in the Rwandan mobile phone market. Because I carefully model consumer and firm objective functions, I can directly measure investment incentives. 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 arguably less selected. And finally, my data covers a long time period with substantial variation in prices and coverage, which may include conditions similar to what would have been observed had a competitor entered earlier.

There are limitations to using data from a monopoly market. 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.

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 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?

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[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.

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 and simulation under monopoly. A forthcoming expanded version of this paper will include sections simulating competition. Section 6 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') 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).

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

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
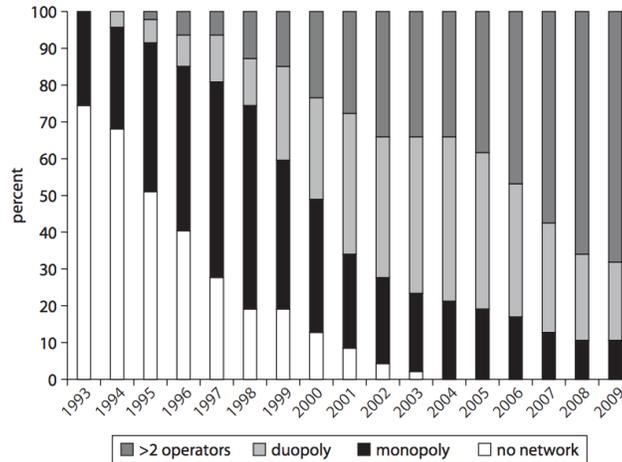
Sources: ITU (2010), regulators, operators.

Source: Williams et al. (2011)

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 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. 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

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.

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.

In an effort to avoid duplication of infrastructure, the Rwandan government required operators to allow others to install equipment on their towers at cost (RURA, 2011); this allowed the new operators to expand their networks much more quickly. 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.
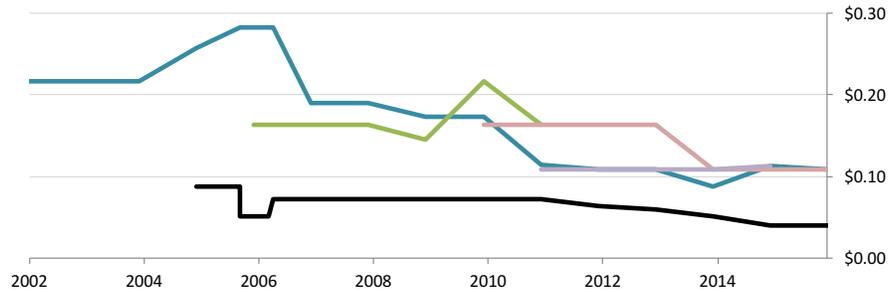
Consumer Choice. The ability of competition to discipline firms depends on how consumers choose between products. Table 2 shows the results of a Research ICT

FIGURE 2. Development of Competition in Rwanda

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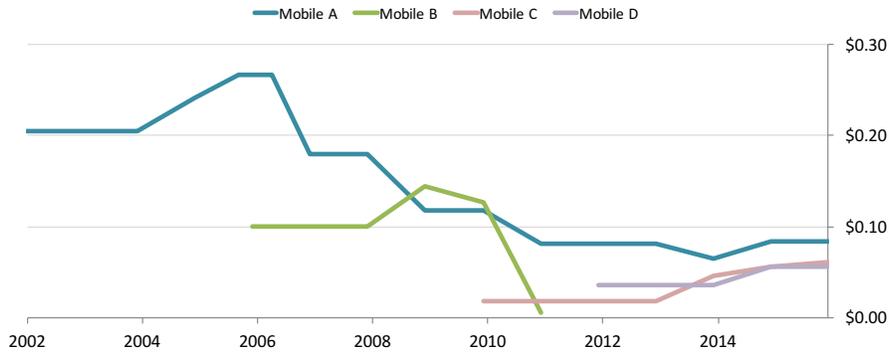
(b) Price, Off Network (30 second peak call. Black: Interconnection Rate per call)

(c) Coverage (Geographic)
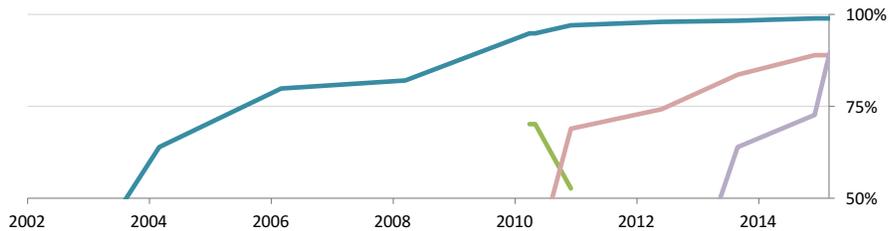
(d) Accounts
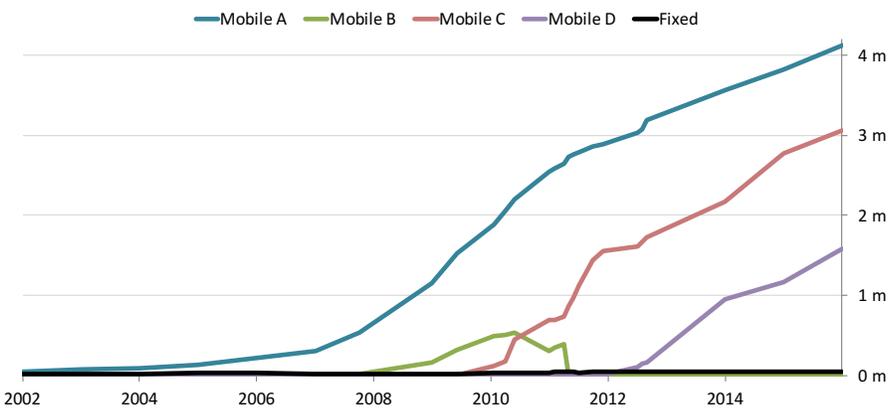
In 2004 the incumbent raised the marginal price of a call while lowering a monthly subscription fee. The subscription fee was abolished in 2005. When the market was essentially a monopoly the number of accounts corresponded closely to the number of individuals with phones. Under competition, some individuals 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.

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.

3. Data

This project uses several data sources:

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

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[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).

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.

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. When adopting, each individual i selects a firm $a_i \in \{0, 1\}$ 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 $G_i = \{j \mid ij \in G\}$ 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:

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

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:

$$c_{ijt} = \beta_{price}p_t^{a_i a_j} + h(\phi_{it}^{a_i}, \phi_{jt}^{a_j})$$

where β_{call} represents call price sensitivity, $p_t^{a_i a_j}$ is the per-second calling price (including any tax) for a call from firm a_i to a_j, and $h(\phi_{it}^{a_i}, \phi_{jt}^{a_j})$ 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. I parameterize the hassle cost as: $h(\phi_{it}^{a_i}, \phi_{jt}^{a_j}) = \beta_{coverage}\phi_{it}^{a_i}\phi_{jt}^{a_j}$.

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:

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

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 $\epsilon_{ijt} \leq \underline{\epsilon}_{ijt} := \frac{\alpha}{1 - \beta_{price} p_t^{a_i a_j} - \beta_{coverage} \phi_{it}^{a_i} \phi_{jt}^{a_j}}$.

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

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

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 vector of firm choices for each individual.

Adoption Decision. Each month i is on network a_i, he receives expected utility from each contact who has a phone:

$$E_\epsilon u_{it}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}, \boldsymbol{x}_{G_i}) = \sum_{j \in G_i \text{ and } x_j \leq t} E_\epsilon u_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) + w \cdot E_\epsilon u_{ji}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a})$$

where x_j represents j's adoption time, 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), and $w \in [0, 1]$ specifies how much recipients value incoming calls. Each month that i is not on the network he receives utility zero.

Conditional on the adoption decisions of others, an individual's adoption decision represents an optimal stopping problem. Individual i chooses when to adopt by weighing the discounted stream of benefits against the price of a handset, represented by index $p_t^{handset}$ (including any tax). Then, if i believes that his contacts will adopt at times $\hat{\boldsymbol{x}}_{G_i}$ on firms $\hat{\mathbf{a}}_{G_i}$, he will consider the utility of adopting at time x, on firm a to be:

$$U_i^{a,x}(\hat{\mathbf{a}}_{G_i}, \hat{\boldsymbol{x}}_{G_i}) = \delta^x \left[\sum_{s=0}^\infty \delta^s E_\epsilon u_{i,x+s}(p_{x+s}, \boldsymbol{\phi}_{x+s}, \{a, \hat{\mathbf{a}}_{G_i}\}, \hat{\boldsymbol{x}}_{G_i}) - \beta_{price} p_x^{handset} + \eta_i^a \right]$$

where an individual's type η_i^a captures heterogeneity in the utility of adopting a phone using operator a that is unobserved to the econometrician. 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.

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:

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

$$\sum_{i \in S} \sum_{t \geq x_i} \delta^t \sum_{j \in G_i \cap S_t} Ed_{ij}(\mathbf{p}_t, \phi_t(\mathbf{z}), \mathbf{a}) \cdot \left[\underbrace{(1 - \tau_{usage,it})p_t^{a_i a_j} \cdot 1_{\{a_i = F\}}}_{\text{Subscribers}} \right.$$

$$\left. + \underbrace{f_{ij} \left[1_{\{a_i \neq F \cap a_j = F\}} - 1_{\{a_i = F \cap a_j \neq F\}} \right]}_{\text{Interconnection}} \right]$$

where $\phi_t(\mathbf{z})$ 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:

$$(4.1) \qquad C_F(\mathbf{p}, \mathbf{z}, \mathbf{a}, \mathbf{x}) = \sum_{z \in \mathbf{z}^F, z \text{ is off grid}} \sum_{t \geq x_z} \delta^t \left[K_{rural} \right] + B^F(\mathbf{p}, \mathbf{z}, \mathbf{a}, \mathbf{x})$$

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

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[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.

with the amount of usage (such as switching equipment, staff, and central operations). I approximate these costs with the linear function:

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

where fc^F represents 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 I consider the effect of counterfactuals, 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).

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

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

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 ($\tau_{usage,it}$):

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

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 operator $a_i \in \{0, 1\}$ and an adoption time $x_i \in [1, ..., \bar{T}]$ to maximize his payoff $U_i^{a_i, x_i}(\mathbf{a}_{G_i}, \boldsymbol{x}_{G_i})$, 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 ($\hat{\boldsymbol{x}}_{G_i} = \boldsymbol{x}_{G_i}$) and operator choices ($\hat{\mathbf{a}}_{G_i} = \mathbf{a}_{G_i}$), 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 operator a_i and adoption time x_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.

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 game where at the beginning of time, 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 operator a_i and adoption date x_i (a complete information static game).

More formally, for a given vector of consumer types $\boldsymbol{\eta}$, 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 a_i maximize utility $U_i^{a_i, x_i}(\mathbf{p}, \boldsymbol{\phi}(\mathbf{z}), \mathbf{x}_{-i}, \mathbf{a}_{-i})$ 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 $\pi_F(\mathbf{p}, \mathbf{z}, \mathbf{a}, \mathbf{x})$, given the competing firm's price sequence and tower construction plan, and individual adoption dates and operator choices

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.

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[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.

5. Estimation and Benchmarks under Monopoly

Estimation under observed near-Monopoly. Model primitives are estimated in Bjorkegren (2017) using maximum likelihood and inequalities.

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 ($a_i \equiv 0$).

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 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

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

|	Firm		Government	Consumer
	Revenue	Profit	Revenue	Utility
Baseline	[165, 181]	[102, 114]	[65, 71]	[244, 263]
Lowered prices	[145, 154]	[34, 37]	[63, 68]	[574, 601]
Total Impact	**-20, -27**	**-68, 77**	**-2, -3**	**330, 338**

(million $)

These figures are preliminary. (The baseline figures differ from Table 4 in their treatment of fees.)

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 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 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,

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[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.

FIGURE 3. Rollout Plans

Observed Incumbent Rollout

2005   2009

No Rural Expansion
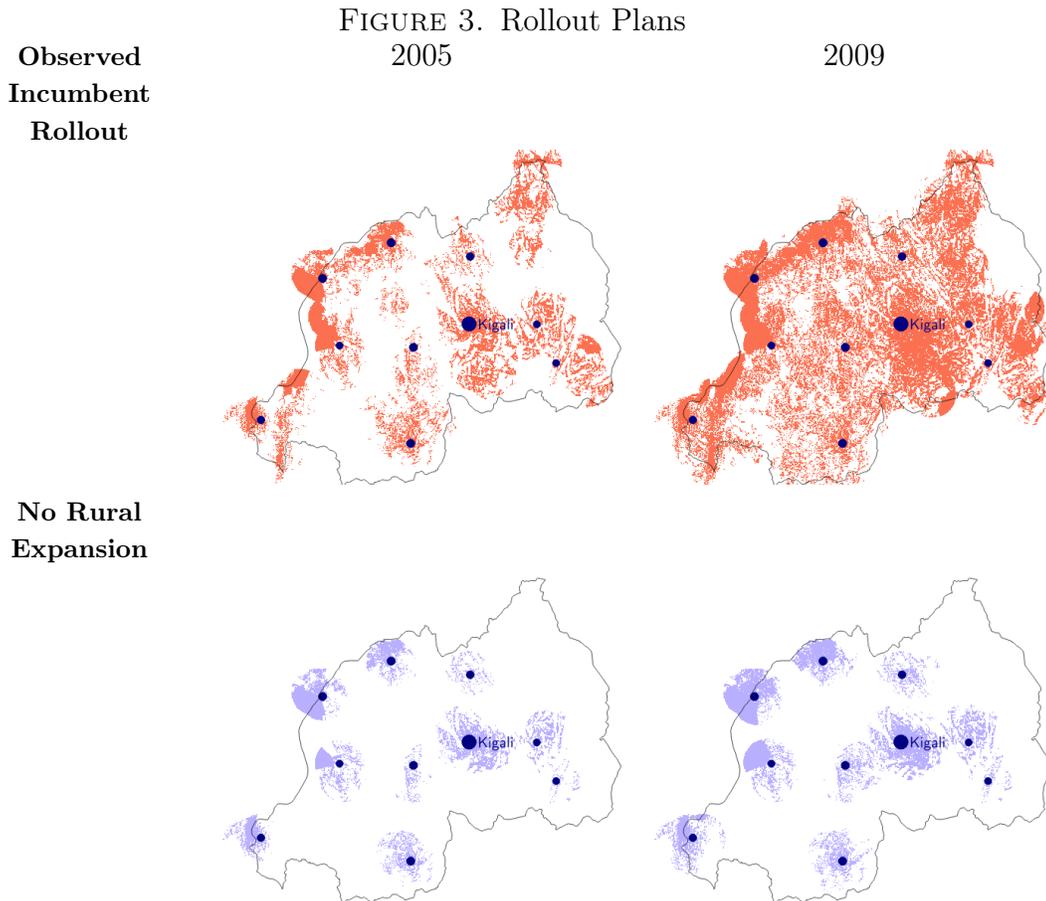
$6m ($5m) from urban-rural connections, and $11m ($14m) from urban-urban connections. While rural areas received improved coverage, a substantial portion of the revenue came from urban-urban links. This is partly because some urban consumers spend time in rural areas and thus directly benefit from coverage (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 $7m >$ $6.8m$ 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 reduce

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

	Utility	**Government Revenue**	**Revenue**				
					By Connection		
	All links	All links	All links	Rural-Rural	Rural-Urban	Urban-Rural	Urban-Urban
Baseline	[236, 253]	[78, 85]	[156, 173]	[25, 28]	[17, 18]	[24, 27]	[90, 100]
No expansion	[163, 177]	[68, 74]	[128, 141]	[18, 20]	[13, 14]	[18, 21]	[79, 86]
Impact	**-73, -76**	**-10, -11**	**-28, -32**	-7, -8	-4, -4	-6, -5	-11, -14
	million $						
Cost of Expansion	6.8	(annualized)					

incentives to expand. An expanded version of this paper which is in progress will evaluate the impact of competition on rural expansion, including the potential for partial rollout and price changes, using the model to simulate a competitive industry.

6. 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 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. A future draft of this paper will simulate the effects of competition under alternative competition rules.

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.

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. (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.

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.

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*.

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.

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 fÃŒr 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.

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

APPENDIX A. ADDITIONAL BACKGROUND

A.1. **Simplifications.** 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 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.[10]

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[10]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.

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).[11] Many other services were available on all networks. I assume any differentiation arising from these services would have been negligible.

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[11]Mobile C introduced a feature that plays music while a caller is waiting for the receiver to pick up.