COMPETITION IN NETWORK INDUSTRIES: EVIDENCE FROM MOBILE TELECOMMUNICATIONS IN RWANDA

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This paper develops a method to analyze the effects of competition policy in a network industry. Competition has mixed effects on incentives to invest: when a network is split between competitors, each captures only a fraction of potential network effects. However, a firm may invest in components that are not shared, to attract customers to its network. I estimate the network utility of adopting a phone based on its subsequent usage, using transaction data from nearly the entire network of Rwandan mobile phone subscribers over 4.5 years. I build a structural model to simulate the equilibrium choices of consumers and network operators, and consider Rwanda's decision to delay the introduction of competition. I find that adding an additional competitor earlier would have reduced prices and can in some cases *increase* incentives to invest in rural towers, increasing welfare by the equivalent of 1.4% of GDP. I analyze the effects of setting different interconnection rates, reducing switching costs through number portability, and introducing competition at different times in the evolution of the network.

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1. Introduction

Many modern technologies have network effects, and as a result lead to industries with natural monopolies (consider Facebook and Google; or in earlier eras, AT&T and Microsoft).[1] How should societies manage these industries?

Governments commonly intervene to spur competition in these networks, in the hope that consumer choice will discipline these industries. Governments can tilt the playing field by making it easier to switch, or by forcing an incumbent to connect its network to entrants (as in telecom, where regulations typically guarantee that consumers can call subscribers of competing networks). Or, governments can split up a dominant firm. However, if societies impose too much discipline, or exert discipline in the wrong ways, firms may not make the investments needed to build these networks.

This paper considers the effects of competition on investment and welfare in the context of mobile phone networks in sub-Saharan Africa. Although voice calls still account for the majority of revenues, mobile phone operators are emerging as the gatekeepers of information, the internet, and, increasingly, financial transactions.[2] The details of how to manage competition have been 'a main bottleneck' (World Bank, 2004), and regulators have little guidance on whether or how to tilt favor, allow consolidation (Moody's, 2015), or split firms (Reuters, 2017).[3]

There is little empirical work to guide policy in any industry with classical network effects, where each node may affect each other node.[4] While there is substantial theory on classical network goods, conclusions depend on empirical parameters.[5] Also, the theory on competition in developed country landline networks (Armstrong, 1998;

[1]As well as emerging networks like Uber, which some are betting will become the central network for coordinating urban transportation.

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

[3]The success of mobile money in Kenya (Suri et al., 2012; Bjorkegren and Grissen, 2018) has proven difficult to replicate: it may be that Safaricom made the large investments to scale M-PESA only because it had no effective competitors in the voice network.

[4]Most empirical work on classical network goods simply measures the extent of network effects; see for example Saloner and Shepard (1995), Goolsbee and Klenow (2002), and Tucker (2008). There is more work on markets with indirect network effects which tend to be more tractable, including platforms and video formats (Ohashi 2003; Gowrisankaran et al. 2010; relatedly, Lee 2013). In those markets, popular platforms tend to be better served by sellers, so adopters benefit indirectly from additional users.

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

Laffont et al., 1998; Laffont and Tirole, 2001) can be inconclusive (Vogelsang, 2013), and mostly omits factors important for growing networks such as investment and network effects in adoption.[6]

A reduced form approach would compare isolated networks in jurisdictions that set different policies. For example, Faccio and Zingales (2017) and Genakos et al. (2018) find that increases in telecom competition are associated with price reductions. However, firms choose prices and investments in anticipation of future policy changes. Depending on these expectations, a reduced form approach could suggest wildly different impacts of the same policy. A policy that lowers incentives to invest could appear to increase it, if firms anticipated that a more dramatic policy would be implemented. These firm expectations are typically unobservable.[7]

A structural approach that models firm objective functions faces three challenges. First, one needs to measure the entire network in order to capture spillover effects. As a result, it is typically not possible to study competitive markets directly: when a market is split, rich network data would need to be linked between all competitors.[8] Second, it is difficult to identify network effects, because each individual's demand is a function of the demand of others in the network. One individual may adopt after a contact adopts because the contact provides network benefits, or because connected individuals share similar traits or are exposed to similar environments. Finally, it is difficult to compute equilibria: firms must anticipate how the effects of an action ripple through the entire network of demand.

This paper overcomes these challenges in the context of Rwanda's mobile phone network. I evaluate the effects of tilting a network industry towards competition, using 5.3 billion transaction records from the incumbent mobile phone operator, which held over 88% of the market. I find that competition policies have enormous welfare consequences. Since my approach requires data only from an incumbent, it can be used by a regulator weighing policy options for an incumbent monopoly.

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

[7]And since most policies are anticipated, policy surprises would not capture how a firm makes investments in anticipation of typical policies.

[8]This data would need to be linked at the node level, which is typically a nonstarter for the operators that own the requisite network usage data.

The Rwandan government initially limited competition to encourage investment in telecommunications. When Rwanda first allowed competition, it followed common practice: firms were not forced to share tower infrastructure, but were forced to interconnect so consumers could call across networks. I study a period of contested monopoly, which has three useful features. First, price varies: the incumbent lowered real calling prices by 76%. But—crucially—the entrant was poorly run and never attained significant market share, so the incumbent's data describes nearly the entire network at the time. Third, the incumbent made large investments in coverage, nearly quadrupling the number of towers and increasing coverage from 60% to 95% of land area.

After this period, the regulator granted an additional license to a well managed competitor, which built out less coverage, charged lower prices, and captured market share. What would have happened if this additional competitor had been granted a license earlier? Would the incumbent still have built coverage in rural areas?

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

First, acknowledging that the utility of owning a mobile phone is derived from its usage, I model the utility of using a phone, using the method and estimates of Bjorkegren (2018). Almost all phones in Rwanda are basic, prepaid mobile phones, and in the period I study mobile money did not exist.[9] I infer the value of each voice connection from subsequent interaction across that connection. This approach bypasses most of the simultaneity issues that result from inferring the value of links from correlations in adoption. Calls are billed on the margin, by the second, so a subscriber must value a connection at least as much as the cost of calls placed across it.[10] Variation in calling prices and the quality of coverage identify the underlying demand curve for communication across each link.

Second, I model the decision to adopt a mobile phone and operator. A phone provides utility by allowing communication with contacts that have phones. Consumers

[9]As of this writing, only 9% of mobile phones in Rwanda are smartphones (ResearchICTAfrica, 2017); in the period I study, almost all phones were basic.

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

choose when to adopt by weighing the increasing stream of utility from communicating with the network against the declining cost of purchasing a handset.[11] I extend Bjorkegren (2018) to allow consumers to select and switch between operators, which may offer different price and coverage paths. I pose hypothetical questions to Rwandan consumers to estimate switching costs and idiosyncratic preferences for the entrant.[12]

Third, I model firm decisions. As a condition for receiving a license, the Rwandan regulator required firms to submit 5 year tower rollout plans. I require firms to commit to a rollout plan as well as a path of calling prices. To limit the multiplicity of equilibria, I require that firms charge the same rate for on- and off-network calls. These represent terms of competition that could be implemented; since the regulator may be able to do better under different terms, my results represent a lower bound of the potential welfare benefits of competition. To evaluate the cost of expanding or shrinking networks, I use engineering cost data collected under mandate by the regulator.

Fourth, to evaluate the impact of policies, I use an iterated best response algorithm to compute equilibria in firm price and rollout plans, and publicly announced adoption dates (the latter builds on Bjorkegren (2018)). I approximately bound the full set of equilibria by exploiting supermodularity in the adoption decision, in a manner similar to Jia (2008).

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

One limitation of this approach is that the network is illuminated by usage, so individuals who do not adopt under baseline conditions are omitted. I model the behavior of nodes in this 'dark' portion of the network, and report results for shorter time horizons before these nodes would have adopted.

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

[12] I corroborate these estimates against an additional validation choice observed in my data, the choice of plan.

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

I find the following:

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

Adding a competitor under the government recommended interconnection rate would have dramatically lowered calling prices: the entrant would have charged 35% of the monopoly rate, and the incumbent 45%, earning a premium for its better coverage.

Adding a competitor would have also altered the incumbent's incentives to invest in rural towers. I quantify three forces. First, lowered prices reduce the total revenue generated from an investment in rural towers by 22-25%. Second, when the network is split but interconnected, some of the benefits spill across networks. 15-16% of the revenue from the incumbent's investment accrues to the entrant, holding fixed operator choices. The entrant pays the incumbent 10% back in interconnection fees, to account for increased usage of its network. In isolation, these two forces would make it unprofitable to build a substantial set of rural towers. However, as is typical in network industries, networks are still differentiated. Because each firm offers its own tower infrastructure, there is a third effect, which in this case dominates. A business stealing effect accounts for 83-85% of the revenue the incumbent earns from building the rural network. Building out rural coverage allows the incumbent to attract the set of marginal urban subscribers who wish to use phones in rural areas but would otherwise subscribe to the lower priced operator. The balance of these forces depends on the interconnection rate; under the government's suggested rate, adding a competitor would have *increased* incentives to invest in rural towers.[13]

On net, adding a competitor under the government's suggested interconnection rates would have increased the net welfare provided by the mobile phone system by up to 60%, an amount equivalent to 1.4% of GDP or 6-7% of official development

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

aid over this time period. This suggests that the industrial organization of emerging networks can have profound welfare implications for the world's poorest economies.

Competition would have been unlikely to develop in absence of interconnection regulation, under these terms of competition. If the incumbent chose the terms of interconnection (and the regulator required operators to charge the same price for on- and off-net calls), the incumbent would have effectively blocked access to its network. This is reminiscent of many network industries that do not endogenously develop compatibility (Katz and Shapiro, 1985).

The particular rules that the regulator selects for the competitive environment can also have substantial welfare consequences. Lower interconnection rates tend to lower prices but also incentives to invest; different reasonable interconnection regimes produce differences in net social welfare equivalent to 0.3% of GDP over this period.

Switching costs have theoretically ambiguous effects on network competition (Farrell and Shapiro, 1988; Suleymanova and Wey, 2011; Chen, 2016). I find that a number portability policy would have shifted a small amount of subscribers and profits to the entrant and slightly increased welfare.

Finally, I show that allowing the entrant to enter near the end of this horizon greatly lessens its effects on the market.

To my knowledge, this represents the first micro-identified empirical analysis of investment or competition that accounts for classical network effects. It builds on the network demand system developed in Bjorkegren (2018). It is related to two papers that analyze how encouraging nodes to adopt affects the adoption of other nodes in a network: Ryan and Tucker (2012) for a corporate videoconferencing system (using transaction records), and Guiteras et al. (2018) for household latrines in Bangladesh (using an RCT).

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 describes simulation, Section 7 presents monopoly benchmarks, Section 8 describes the applicability of the model to competition, and Section 9 describes the results of introducing competition. Section 10 concludes.

2. Context

Developing country phone systems. Between 2000 and 2011, the number of mobile phone subscriptions in developing economies increased from 250 million to 4.5 billion (ITU, 2011). Handsets were initially expensive, but became accessible even to the poor as component costs decreased. (In 2005, the cheapest mainstream handset in Rwanda cost roughly $70, or 3.5 months of the mean person's consumption; by 2009 handsets were available for $13.) As poor consumers began to be able to afford phones, operators expanded coverage to increasingly remote regions.

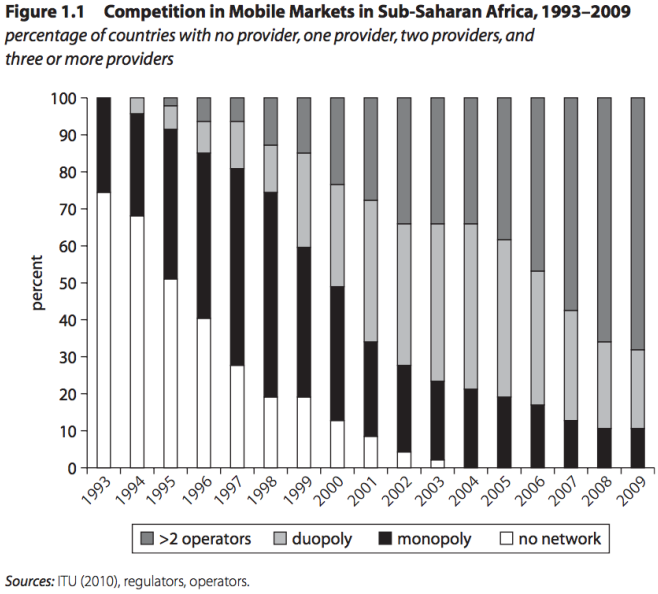
As these networks grew, regulators quickly realized that it may be possible to obtain better performance from the sector by allowing multiple operators to compete in providing service.

However, an entrant phone network will be of limited use unless it can connect to an existing phone system. Left to the market, incumbents typically demand prohibitively high fees for interconnection, preventing competition (the 'one way' access problem). Thus, regulators typically intervene and determine the terms of interconnection. When network sizes are balanced, theory suggests that the problem is lessened (the 'two way' access problem) but ongoing regulation is required, since negotiated interconnection rates can be an instrument of collusion (Armstrong, 1998; Laffont et al., 1998). Theory suggests that interconnection rates be set to a function of the cost of connecting a phone call, and the World Bank (2004) model represents a benchmark. But different theoretical models suggest different optimal interconnection rates, and most telecom theory is designed for mature developed country networks, and does not consider how policies affect growth of the network.

Thus, developing societies face two large questions: how much competition should regulators promote? And how should regulators shape the competitive landscape?

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 while three countries had net exit.

FIGURE 1. Telecom Competition



Source: Williams et al. (2011)

There is also little consensus on the optimal ground rules for competition. Table 1 summarizes the diversity of 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.

Rwanda. In the aftermath of the genocide and civil war, the Rwandan government in 1998 granted a license to a multinational operator to develop and run a mobile phone system (Operator A); it was understood that this license would be exclusive for a limited period 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

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%	
...based on costs	43%	
...based on benchmarks	38%	
Interconnection charges are regulated	97%	
...based on costs (LRIC or FDC)	71%	
...based on benchmarks	43%	
...asymmetrically between operators	31%	
...using multiple zones	34%	
...using multiple timebands	56%	
Infrastructure is shared	100%	
...by mandate	62%	
...including active infrastructure (electronics)	48%	

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.

20% of market share for a brief period after the end of my data. In 2011, its license was revoked for failure to meet obligations.[14]

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 prices.[15]

[14]The Registrar General, Louise Kanyonga said, "The company was mismanaged and their liabilities far outweigh their assets... This has been a real learning experience for our government. We need to ask how this happened."

[15]The Rwandan government sought to avoid duplication of infrastructure and in 2011 required operators to share infrastructure at cost, as identified in the study RURA (2011). This ex post sharing mandate allowed the new operator to quickly expand its network, but Operator A expressed concerns that it could chill future investment. (The government used a new, ex-ante sharing model for the next major infrastructure investment: it granted a license to a South Korean firm to build a single, wholesale 4G network, which was leased out to the operators.) In my simulations I do not apply the infrastructure sharing mandate.

In 2011 a license was granted to Operator D, which purchased the assets of the Operator B and took over its license. After a second interconnection dispute, the regulator again hired a consultant, 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; PwC, 2011; RURA, 2009).

In 2018, Operator C and D merged, bringing the market back to a duopoly.

See Figure 2 for the evolution of handset prices, accounts, calling prices, and coverage. The coverage plot shows that despite being able to build on the incumbent's towers, entrants' networks offer less complete coverage.

This paper uses data from the period 2005-2009. The calling price plot shows the baseline calling price, and foreshadows the result of a focal counterfactual where Operator C is granted a license in 2005 at the analyst recommended interconnection rate of $0.07 per minute.

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

In Rwanda, almost all phone plans are prepaid.[16] Handsets are standard, imported models; local prices track global trends. Most are purchased from independent sellers: operator handset sales records account for only 10% of total handsets activated during the period of my data. I consider the handset market as perfectly competitive, with availability and prices unaffected by the market for cellular service.

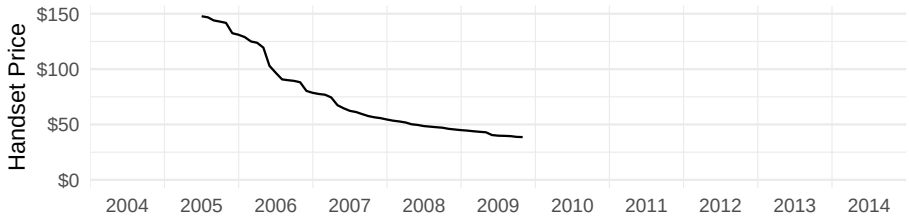
During this period, phones were used primarily for voice calls. Mobile money did not exist in Rwanda during this period. I do not explicitly model utility from SMS, missed calls, international calls, and calls from payphones.[17] Any value these omissions provide to the primary operator's subscribers will be captured in a residual when I estimate the adoption decision.

[16] In 2007-8, no surveyed phone owners received their handset with a contract.

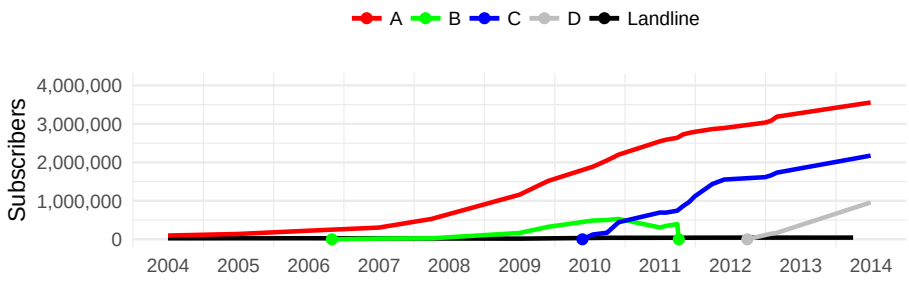
[17] From the data it is not possible to match the sender and receiver of a given SMS. Though important in other contexts, in Rwanda text messaging or SMS was high priced ($0.10 per message) and represented less than 13% of revenue and 16% of transactions. Only calls that are answered incur a charge;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

FIGURE 2. Development of Telecommunications in Rwanda

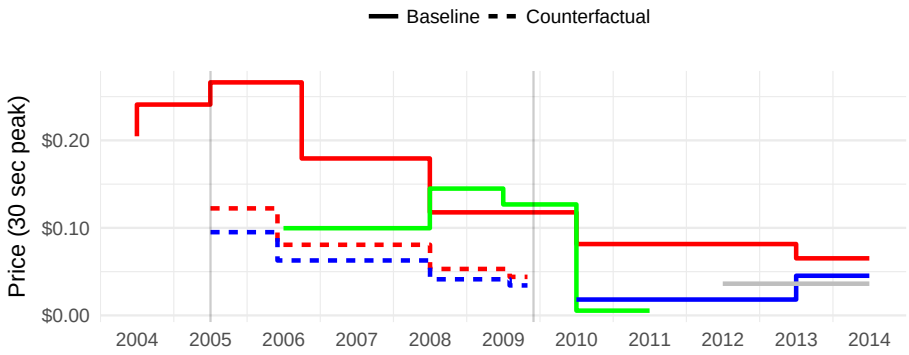
(a) Handset Price (real, quality adjusted index)



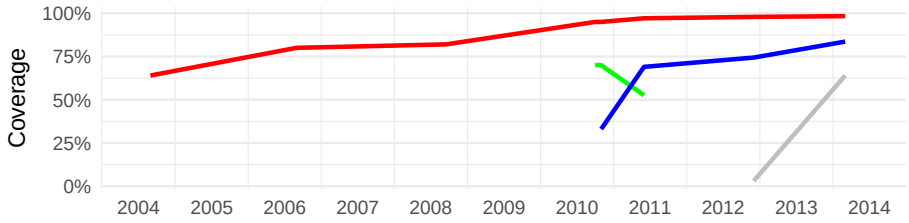
(b) Accounts



(c) Calling Price, On Network (30 second peak call, nominal)



(d) Coverage (geographic)



Handset prices reported during the years I have data on prices and quantities. I report baseline calling prices and the prices from a focal counterfactual where Operator C enters in 2005 with an interconnection rate of $0.07 per minute. Sources: archived operator websites and regulator reports.

TABLE 2. Mobile Phone Usage among Owners in sub-Saharan Africa

	2007-8		2010-11	
	Rwanda	SSA**	Rwanda	SSA*
Received phone with a contract	0%	3%	3%	11%
Use phone for				
Voice calls	95%	98%	100%	99%
Music or radio	6%	14%	35%	46%
Taking photos or videos	5%	15%	24%	39%
Email	2%	3%	13%	14%
Sending or receiving money	-	-	18%	18%
Browsing Internet	-	-	15%	17%
Facebook or other social network	-	-	14%	16%
Apps (downloaded)	-	-	6%	15%

Source: RIA household surveys 2007-2008 and 2010-2011. *: Representative samples of mobile phone owners in Cameroon, Ethiopia, Ghana, Kenya, Mozambique, Namibia, Nigeria, Rwanda, South Africa, Tanzania, and Uganda; **: also Benin, Botswana, Burkina Faso, Cote d'Ivoire, Senegal, and Zambia. A dash indicates that question was not asked in that survey round.

Consumers report selecting operators mostly based on coverage (51% of respondents, multiple responses allowed), which network their contacts are on (37%), the range of services offered (27%), and price (20%).[18] I develop a model to capture the key differentiators (coverage and pricing). 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 (for more information see Supplemental Appendix):

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 400,000 in January 2005 and growing to 1.5 million in May 2009. For each transaction, the data reports: anonymous identifiers for sender and receiver,

[18]See Supplemental Appendix: Operator Differentiators.

corresponding to the phone number and handset, time stamps, the location of the cell towers used, and call duration.[19] I aggregate durations to the monthly level.

Operator costs: Following common practice, the Rwandan regulator regularly collects cost data from operators in order to ensure interconnection rates are 'derived from relevant costs' (RURA, 2009). I use long run incremental costs from a study conducted for Rwanda by international consultants (PwC, 2011), which was crosschecked against regional and international benchmarks.

Coverage: A rollout plan, $\mathbf{z} = \{(t_z, x_z, y_z)\}_z$, is defined by tower build dates and geographical coordinates. I consider the baseline rollout, $\mathbf{z}_{full}$, as well as counterfactual rollouts that trim low revenue rural towers. I create coverage maps by computing the areas within line of sight of the towers operational in each month, a method suggested by the operator's network engineer. Elevation maps are derived from satellite imagery recorded by NASA (Jarvis et al., 2008; Farr et al., 2007).

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

Handset prices: I create a monthly handset price index $p_t^{handset}$ based on 160 popular models in Rwanda, adjusting for quality and weighting each model by the quantity activated on the network.

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

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 develop a model of handset adoption and usage, extended from Bjorkegren (2018) to allow for competition. Since the utility of owning a phone is derived from making calls, I begin in reverse, with a model of usage.

Consumers. Let $\bar{G}$ be the communication graph of Rwanda (a directed social network), with N nodes representing all individuals in the country. A directed link $ij \in \bar{G}$ indicates that i would have a potential desire to call j via phone. I assume that links are fixed.

Let $S_t \subseteq N$ be the set of individuals with phones in month t. Since I observe only individuals who adopt by the end of my data T, I observe the set $S_T \subseteq N$. This omits the small number of individuals who subscribed to the incumbent's first competitor, less than 12% of the market; I assume that these individuals' usage remains the same in any counterfactual.[20] It also omits any other 'dark' nodes $i \in N \backslash S_T$ who may have adopted if conditions were more favorable. Since I only observe a link if a call was placed, I observe the subgraph, $G^T \subseteq \bar{G}$, where $ij \in G^T$ if i has called j by period T.[21] As shorthand, define $G_i = \left\{ j \,\middle|\, ij \in G^T \right\}$ as i's set of contacts. I report simulation results for shorter time horizons $\tilde{T} \leq T$, during which the omission of dark nodes would not affect results (discussed further in the Simulation section).

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

[20] This may result in underestimating the effects of competition, if it induces switching away from Operator B. Operator B used CDMA, a technology incompatible with the other GSM networks, and thus it would have been costly for individuals to switch. In my data I do not observe calls between Operators A and B.

[21] This will miss any links between subscribers where there is a latent desire to communicate but no call has been placed by T ($G^T \subseteq \bar{G}^T$). See Supplemental Appendix of Bjorkegren (2018).

Calling decision. Operators are interconnected, so in each period t that individual i has a phone, he can call any contact j that subscribes to either operator, $j \in G_i \cap S_t$. i draws a communication shock $\epsilon_{ijt} \overset{iid}{\sim} F_{ij}$ representing a desire to call j, and chooses a total duration $d_{ijt} \geq 0$ for that month, earning utility:

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

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

I model the benefit of making calls as:

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

where the first term represents a linear benefit; $\gamma > 1$ controls how quickly marginal returns decline, and α controls the intercept of marginal utility, and thus the fraction of months for which no call is placed.[22]

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

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

where $p_t^{a_{it} a_{jt}}$ is the per-second calling price for a call from firm a_{it} to a_{jt} (including any tax). In order to bound equilibria, I assume the regulator does not allow firms to charge different prices for off-net calls, so that $p_t^{a_{it} a_{jt}} = p_t^{a_{it}}$ (discussed in the Simulation section). $\beta_{coverage} \phi_{it}^{a_{it}} \phi_{jt}^{a_{jt}}$ represents the hassle cost when the caller or receiver have imperfect coverage. An individual's coverage $\phi_{it}^a \in [0, 1]$ is derived from the fraction of the area surrounding his most used locations receiving cellular coverage in month t under firm a's rollout plan.

The benefit of an additional second of duration across a link is decreasing, so i will call j until the marginal benefit equals the marginal cost, at duration:

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

[22] This functional form was chosen to satisfy 8 reasonable properties for the utility from telephone calls; see Bjorkegren (2018).

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

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

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

and provide expected utility:

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

If they are valued, incoming calls provide utility:

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

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

(3)

$$Eu_{it}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}, \boldsymbol{x}_{G_i}) = \sum_{j \in G_i \text{ and } x_j \leq t} [Eu_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) + w \cdot E\tilde{u}_{ji}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a})] - s \cdot 1_{\{a_{it} \neq a_{it-1}\}}$$

where x_j represents j's adoption time, $w \in [0, 1]$ specifies whether recipients value incoming calls, and s represents the cost of switching operators.[23]

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

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

where an individual's type (η_i^0, η_i^1) represents heterogeneity in the anticipated utility of using a phone on each operator that is unobserved to the econometrician. Types need not be mean zero, but to make simulation tractable I do require that each

[23]This would include the cost of changing accounts (swapping SIM cards and adjusting any settings), and notifying contacts about the change in phone number.

individual's type is constant over time and across counterfactuals. Each month that i does not have a phone he receives utility zero.

Adoption decision. Conditional on the 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, $p_t^{handset}$ (inclusive of any tax). He believes his contacts will adopt at times $\boldsymbol{x}_{G_i}$ using operator sequences $\mathbf{a}_{G_i}$, and that in period $x > t$, the handset price will be $E_t p_x^{handset}$, a deterministic function that is described in the following section. He expects the utility of adopting at time x with operator sequence $\mathbf{a}_i$ to be:

$$E_t U_i^{\mathbf{a}_i,x}(\mathbf{p}, \boldsymbol{\phi}, \boldsymbol{x}_{G_i}, \mathbf{a}_{G_i}) = \delta^x \left[\sum_{s \geq x}^{\infty} \delta^{s-x} E\hat{u}_{is}(\mathbf{p}_s, \boldsymbol{\phi}_s, \mathbf{a}, \boldsymbol{x}_{G_i}) - E_t p_x^{handset} \right] \tag{4}$$

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

$$\min\ x_i\ s.t. \left[\max_{\mathbf{a}_i} E_{x_i} U_i^{\mathbf{a}_i,x_i}(\mathbf{p}, \boldsymbol{\phi}, \boldsymbol{x}_{G_i}, \mathbf{a}_{G_i}) \geq \max_{s > x_i, \tilde{\mathbf{a}}_i} E_{x_i} U_i^{\tilde{\mathbf{a}}_i,s}(\mathbf{p}, \boldsymbol{\phi}, \boldsymbol{x}_{G_i}, \mathbf{a}_{G_i}) \right] \tag{5}$$

and selects operator sequence $\mathbf{a}_i$ to maximize utility. In counterfactuals, I allow consumers to delay adoption beyond the end point of the data $\bar{T} > T$, but report outcomes only up to a shorter horizon $\tilde{T} \leq T$.

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

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

which is net of calling, handset, and hassle costs. I compute handset costs assuming each handset is provided by a competitive market at marginal cost, and is sold back at the end of the data at the prevailing price.

This will underestimate consumer surplus if given conditions (prices $\mathbf{p}$, coverage $\boldsymbol{\phi}$, and adoption $\mathbf{a}$ and $\boldsymbol{x}$), any dark nodes ($i \in N \backslash S_T$) or latent links ($ij \in \bar{G} \backslash G^T$) would become active before $\tilde{T}$. I assess this in the Simulation section.

Firms. Each firm F commits to a path of calling prices $\mathbf{p}^F$ and a tower building plan $\mathbf{z}^F$ to maximize net present profits through horizon $\tilde{T}$:[24]

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

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

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

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

Firm F incurs costs:

$$\begin{aligned} C_F^{\tilde{T}}(\mathbf{p}, \boldsymbol{z}, \mathbf{a}, \mathbf{x}) \quad &= K_{rural} \cdot \sum_{z \in \mathbf{z}^F, z \text{ is off grid}} \sum_{t \geq x_z}^{\tilde{T}} \delta^t \\ &+ \sum_{i \in S_T} \sum_{t \geq x_i}^{\tilde{T}} \delta^t \sum_{j \in G_i \cap S_t} Ed_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t(\mathbf{z}), \mathbf{a}) \cdot (ic_{L_i, onnet_{ij}}^{out} \cdot 1_{\{a_{it}=F\}} + ic_{L_j, onnet_{ij}}^{in} 1_{\{a_{jt}=F\}}) \\ (6) \quad &+ \sum_{t \geq \min\{x_z | z \in \mathbf{z}^F\}}^{\tilde{T}} \delta^t \left(fc^F + lc^F \right) \end{aligned}$$

K_{rural} represents the annualized cost of owning and operating a rural tower.[25] $ic_{L_i, onnet_{ij}}^{direction}$ is the incremental cost of operating a network that sends or receives an additional second, including switching equipment, staff, central operations, and costs of capital. I allow the cost to vary by the direction of the call, whether the two parties are on the same network, and whether each subscriber is primarily urban or rural ($L_i \in \{\text{urban}, \text{rural}\}$). Each month that its network is operational, operator F

[24] The firm does not factor in that its actions affect the stock of subscribing consumers at $\tilde{T} + 1$. Results will be similar to the case where the firm expects subscribers to have an opportunity to sell their handset at the prevailing price at $\tilde{T}$ or switch operators costlessly at $\tilde{T} + 1$.

[25] I define a tower as urban if it covers Kigali or one of Rwanda's 5 largest towns; a subscriber is defined as urban if his most used tower is urban.

also incurs fixed cost fc^F and license fee lc^F regardless of the size of its operations. I infer costs from two studies commissioned by the regulator, described in Estimation.

Government. The government decides whether to grant a license to the entrant firm, and if so, sets the interconnection policy f_{ij} and license fee lc^F. It earns revenue:

$$R_G^{\tilde{T}}(\mathbf{p}, \boldsymbol{z}, \mathbf{a}, \mathbf{x}) = \sum_{F \in \{0,1\}} \sum_{t \geq \min\{x_z | z \in \mathbf{z}^F\}}^{\tilde{T}} \delta^t lc^F + \sum_{i \in S_T \text{ and } x_i \leq \tilde{T}} \left[\delta^{x_i} \tau_{ix_i}^{handset} p_{x_i}^{handset} + \sum_{t \geq x_i}^{\tilde{T}} \left(\delta^t \tau_{it}^{usage} \sum_{j \in G_i \cap S_t} p_t^{a_{it} a_{jt}} \cdot Ed_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) \right) \right]$$

This includes revenue from taxes on adoption ($\tau_{it}^{handset}$) and usage (τ_{it}^{usage}); I hold these fixed at Rwanda's rates at the time (48% tax on handsets and 23% tax on usage). I do not take a stand on whether the government maximizes welfare, revenue, or another objective.

Equilibrium. An equilibrium reconciles firm choices with the network of consumer choices.

As a condition for receiving or renewing a license, regulators commonly require mobile telecoms to submit tower rollout plans; in Rwanda, these specify investments over a horizon of 5 years.[26] To make simulation tractable, I assume the regulator requires firms to commit to a plan through $\tilde{T}$ that specifies tower rollout and also a path of prices.

At the beginning of time, the interconnection terms $\boldsymbol{f}$ are set, either by the incumbent (unregulated interconnection) or the government (regulated interconnection). There tend to be multiple consumer adoption equilibria; I exploit supermodularity in the structure of the problem to study an approximately highest and approximately lowest equilibrium. Firms anticipate which equilibrium consumers will coordinate on and are aware of consumer types $\boldsymbol{\eta}$. Firms simultaneously announce their price sequence $\mathbf{p}^F$ and tower construction plan $\mathbf{z}^F$, and each individual announces their adoption date x_i and operator sequence $\mathbf{a}_i$. More formally:

[26] These appear to be enforced: in 2007, Operator B was fined for failing to comply with its coverage and rollout plan. See Supplemental Appendix for requirements attached to the 2008 rollout plan.

Given consumer types $\boldsymbol{\eta}$, interconnection terms $\boldsymbol{f}$, and horizon $\tilde{T}$, an **ε-equilibrium** $\boldsymbol{\Gamma}(\boldsymbol{\eta}, \boldsymbol{f}, \tilde{T})$ is a tuple $(\mathbf{p}^0, \mathbf{p}^1, \mathbf{z}^0, \mathbf{z}^1, \mathbf{a}, \mathbf{x})$ such that:

- $(\mathbf{x}, \mathbf{a})$ is a network adoption partial equilibrium given $(\mathbf{p}^0, \mathbf{p}^1, \mathbf{z}^0, \mathbf{z}^1)$
- Each firm F cannot profit more than ε by deviating from price sequence $\mathbf{p}^F$ and tower construction plan $\mathbf{z}^F$ through $\tilde{T}$, given the competing firm's price sequence and tower construction plan, interconnection terms, and individual adoption dates and operator choices:

$$\pi_F^{\tilde{T}}(\mathbf{p}^F, \mathbf{p}^{-F}, \boldsymbol{z}^F, \boldsymbol{z}^{-F}, \mathbf{a}, \mathbf{x}, \boldsymbol{f}) \geq \pi_F^{\tilde{T}}(\mathbf{p}^{F*}, \mathbf{p}^{-F}, \boldsymbol{z}^{F*}, \boldsymbol{z}^{-F}, \mathbf{a}, \mathbf{x}, \boldsymbol{f}) - \varepsilon \text{ for all } \mathbf{p}^{F*} \text{ and } \mathbf{z}^{F*}$$

Given firm choices $(\mathbf{p}^0, \mathbf{p}^1, \mathbf{z}^0, \mathbf{z}^1)$ and a vector of consumer types $\boldsymbol{\eta}$, a **network adoption partial equilibrium** $(\mathbf{x}, \mathbf{a})$ is defined by adoption dates $\boldsymbol{x} = [x_i]_{i \in S_T}$ and operator choices $\mathbf{a} = [\mathbf{a}_i]_{i \in S_T}$ such that:

- Each initial adopter $i \in S_0$ selects operator sequence $\mathbf{a}_i \in \{0,1\}^{\bar{T}}$ optimally according to Equation 5, with beliefs consistent with his contacts' decisions
- Every other observed adopter $i \in S_T \backslash S_0$ selects adoption date $x_i \in \{1, ..., \bar{T}\}$ and operator sequence $\mathbf{a}_i \in \{0,1\}^{\bar{T}-x_i}$ optimally according to Equation 5, with beliefs consistent with his contacts' decisions

Expectations. Individuals correctly forecast call prices p_x, coverage $\boldsymbol{\phi}_x$, and their contacts' adoption dates $\boldsymbol{x}_{G_i}$, and operator choices $\mathbf{a}_{G_i}$. Because a handset becomes sunk at the time of purchase, forecasts of future prices can sway the adoption decision. I assume that at each period t, individuals learn the current handset price and expect the price in future periods to decline at an exponential rate consistent with the overall decline over this period:

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

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

Together, this notion corresponds to an equilibrium of a game where each individual adopts at the first sufficiently attractive date, based on the expected path of handset prices, and the actual decisions of contacts. It implies that individuals do not anticipate how later adopters will respond to their actions, because later adopters

may not condition their strategy on actions in prior periods.[27] It also introduces a slight inconsistency: when i decides whether to adopt in period x_i, he does not know future handset prices, but does know the adoption dates and operator choices of his future contacts, which will have incorporated future handset prices. I tolerate this inconsistency in order to have a computable notion of equilibrium.

If at the point of adoption, an individual forecasts differently than specified here, the error will be captured in his type (η_i^0, η_i^1), as long as the error is fixed across time and counterfactuals.[28]

This notion allows for rich behavior: a perturbation of utility that causes one individual to change their adoption date can shift the equilibrium, inducing ripple effects through potentially the entire network. Firms internalize revenue from network effects in their own networks, but not from network effects that spill over into competing networks (except to the extent that these are partially recovered through interconnection fees).

5. Estimation

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

Consumer decisions when there is a single operator. In the observed monopoly environment, 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, and how that value changes with prices and coverage. The adoption decision reveals any residual factors affecting adoption with the incumbent (individual type η_i^0). I use the estimation method and estimates of Bjorkegren (2018), described here.

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

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

[28] To assess the importance of forward looking behavior, Bjorkegren (2018) also estimates and simulates results under a myopic model where individuals do not consider the future in their adoption decision, for the monopoly case.

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

where θ_{ij} is the value of the link if j also adopts. It is difficult to estimate θ_{ij} from correlations in adoption: each individual's adoption depends on the other's, as well as any unobserved shocks, which are likely to be correlated (Manski, 1993). Approaches that instrument for adoption tend to rely on very particular variation, and yield crude measures of value.[29]

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

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

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

My approach requires that the latent desire to communicate (ϵ_{ijt}) is uncorrelated with costs (p_t^0 and $\phi_{it}^0 \phi_{jt}^0$, which both improve over time). As the network grows, the composition of subscribers changes, and the operator may adjust prices and coverage in response. I absorb compositional changes by using only within-link variation to estimate the response of usage to costs. My identification assumption implies that the value of communicating with a particular contact does not otherwise trend over time, or depend on who else has adopted. I test this assumption by analyzing changes in calling patterns across links; results are consistent with these factors being negligible.[30] Apart from these restrictions, communication shocks can be arbitrarily correlated between any links in the network.

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

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

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

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

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

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

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

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

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

These are combined into the log-likelihood function:

(7)

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

The full sample has 1,525,061 nodes, 414.5 million links, and a total of 15 billion link-month duration observations. The calling decision has 7 types of parameters. I assume that the shape and sensitivity parameters are common to all links (γ, α,

β_{cost}, $\beta_{coverage}$). I allow the parameter scaling the shock distribution (σ_i), and the probability of no call at any price ($1 - q_i$) to vary at the individual level. I allow the shock distribution to be shifted at the link level, with structure:

$$\mu_{ij} = \mu_i + \mu_{\max(x_i,x_j),\overline{\phi_{it}\phi_{jt}}}$$

which includes an individual mean term μ_i, and a cost fixed effect for each combination of link adoption date ($\max\{x_i, x_j\}$) and average coverage ($\overline{\phi_{it}\phi_{jt}}$), discretized to 519 combinations. This term ensures that price and coverage sensitivity are identified off of within-link changes in calling.[31]

Bjorkegren (2018) uses a two step maximum likelihood procedure to estimate all 4.6 million parameters, exploiting the fact that conditional on the common parameters and cost fixed effects, an individual's distribution parameters affect only his own likelihood.

Adoption decision. The adoption decision bounds an individual's type under the incumbent, η_i^0. Consider the utility i would have received had he adopted a different month. At time x_i, i bought a handset rather than waiting K months. Holding fixed the actions of others, Equation 5 implies $E_{x_i}U_i^{0,x_i}(\boldsymbol{x}_{G_i}, \mathbf{0}) \geq E_{x_i}U_i^{0,x_i+K}(\boldsymbol{x}_{G_i}, \mathbf{0})$. This implies that the expected utility of being on the network during the following K months must have exceeded the expected drop in handset prices:[32]

$$\sum_{s=0}^{K-1} \delta^s E u_{ix_i+s}(p_{x_i+s}, \boldsymbol{\phi}_{x_i+s}, \boldsymbol{x}_{G_i}, \mathbf{0}) + (1-\delta^K)\eta_i^0 \geq p_{x_i}^{handset} - \delta^K E_{x_i} p_{x_i+K}^{handset} \tag{8}$$

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

[31]To see how this formulation addresses the selection issue, note that the numerator inside the standard normal CDF in $F_{ij}[\epsilon(d)]$ can be written: $\ln\left(d^{\gamma-1} + \alpha\right) - \ln\left(1 - \beta_{cost}\left(p_t + \beta_{coverage}\phi_{it}\phi_{jt}\right)\right) - \mu_{ij}$. Consider the decomposition $\mu_{ij} = \mu_i + e_{ij}$ where μ_{ij} is the true link mean and e_{ij} is an error. If the estimated specification only includes μ_i, and if e_{ij} is correlated with p_t or $\phi_{it}\phi_{jt}$, then estimates of β_{cost} and $\beta_{coverage}$ may be biased. While each link faces the same price series over time, links that join the network later face lower prices on average: the price path faced by a link is summarized by the link's adoption date. Each link faces a different coverage path; I approximate these with the average joint coverage using 10 bins.

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

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

(9)
$$\sum_{s=0}^{\tilde{K}-1}\delta^s Eu_{i,x_i-K+s}(p_{x_i-K+s},\boldsymbol{\phi}_{x_i-K+s},\boldsymbol{x}_{G_i},\mathbf{0})+(1-\delta^{\tilde{K}})\eta_i^0 \leq p_{x_i-K}^{handset}-\delta^{\tilde{K}}E_{x_i-K}p_{x_i-K+\tilde{K}}^{handset}$$

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

(10)
$$\underline{\eta}_i^0 = \frac{1}{1-\delta^K}\left[p_{x_i}^{handset}-\delta^K E_{x_i}p_{x_i+K}^{handset}-\sum_{s=0}^{K-1}\delta^s Eu_{i,x_i+s}(p_{x_i+s},\boldsymbol{\phi}_{x_i+s},\boldsymbol{x}_{Gi},\mathbf{0}) \right]$$
$$\bar{\eta}_i^0 = \max_{\tilde{K}>0}\left[\frac{1}{1-\delta^{\tilde{K}}}\left[p_{x_i-K}^{handset}-\delta^{\tilde{K}}E_{x_i-K}p_{x_i-K+\tilde{K}}^{handset}-\sum_{s=0}^{\tilde{K}-1}\delta^s Eu_{i,x_i-K+s}(p_{x_i-K+s},\boldsymbol{\phi}_{x_i-K+s},\boldsymbol{x}_{Gi},\mathbf{0}) \right]\right]$$

I set $K=2$ months.[33] Note that the future after $x_i+\max(K,\tilde{K}-K)$ cancels out of these expressions: as long as the next preferred adoption date occurs within the data, results are not sensitive to the evolution of the network beyond that point. These conditions are necessary for equilibrium and are valid in the presence of multiple equilibria. During months that extra fees were charged, I incorporate the fee schedule.[34] I set the discount factor to the inverse of the average real interest rate in Rwanda over this period: $\delta=(\frac{1}{1.07})^{1/12}\sim 0.9945$ (source: World Bank). I am able to recover η_i^0's for 0.8m nodes adopting between $x_i\in[K,T-K]$.[35]

Validation. As a robustness check, Bjorkegren (2018) tests whether the value implied by calls corresponds with the value implied by adoption. I form Equations 8 and 9

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

[34] Before June 2007, subscribers needed to add roughly \$4.53 in credit per month to keep their account open; I factor this in as a hassle cost. Actually opening an account entails purchasing a SIM card, which cost roughly \$1 itself plus the cost of an initial top up. See Supplemental Appendix of Bjorkegren (2018).

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

into moment inequalities. I use instrumental variables that shift adoption based on the cost of providing coverage to different areas due to Rwanda's hilly geography, in a manner similar to Yanagizawa-Drott (2014), as well as in the fraction of contacts who join in response to a government adoption subsidy program. Results suggest these valuations of calls and adoption are consistent under $w = 0$ (consumers value one dollar of call utility between \$1.02-1.17 of handset price), but under $w = 1$, the utility of calls is double counted. I proceed with $w = 0$ as the base specification.[36]

Consumer decisions with multiple operators. Behavior under monopoly provision reveal how individuals trade off access to links, prices, and coverage. As a result, my approach could be used by a regulator evaluating how to manage an incumbent monopoly with only data from that market. However, since Rwanda did later add an entrant, I am able to estimate additional parameters. To estimate the costs of switching, and idiosyncratic preferences for the entrant, I posed hypothetical questions in a survey of mobile phone owners in Rwanda (see Supplemental Appendix for details).

Consumers find it a hassle to switch operators, especially when a switch entails changing phone numbers. Based on an incremental switching exercise, I estimate a switching cost of $s = \$36.09$, corresponding to 6.8 months of household average airtime spending in 2010 (EICV). The switching cost drops to \$18.51 if consumers can keep their phone numbers when changing operators, which I consider as a counterfactual policy. To assess the quality of hypothetical responses, I ask respondents to make an additional hypothetical choice that is analogous to a choice observed within my data. I estimate the cost of switching between plans on the same operator, and find that the estimate derived from data and that derived from hypothetical responses do not differ significantly at the 1% level (see Supplemental Appendix).

Consumers have a very slight idiosyncratic preference for the incumbent, holding fixed prices and coverage. I isolate this preference with an incremental switching exercise, which finds a difference with mean $m(\eta_i^0 - \eta_i^1) = \$2.45$ (\$0.01 per month), and standard deviation $\sigma(\eta_i^1 - \eta_i^0) = \$6.72$. These preferences are not correlated with observables, and when asked to explain their choices, the most common response was a

[36]Bjorkegren (2018) finds that results do not differ substantially for several monopoly counterfactuals under the assumption $w = 1$; I do not test this in this paper because it would double very long computation times.

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

Firm costs. I infer firm costs from two studies commissioned by the Rwandan regulator.

I infer incremental costs $ic^Y_{L_i,onnet_{ij}}$ and fixed costs fc^F from PwC (2011), a confidential cost study commissioned to set interconnection rates.[37] This study constructs a detailed engineering breakdown of the network, using cost estimates obtained from operators and crosschecked against international benchmarks. It combines the costs of towers, switching equipment, staff, central operations, and capital to compute the Long Run Incremental Cost (LRIC) of sending or receiving an additional second of voice calls. I break down these costs to better match my setup, in three ways. First, the study inflates the incremental cost estimates with a proportional markup to cover fixed costs of operating the network. I report these fixed costs separately, by multiplying each firm's total incremental cost by the same proportional markup used in the study (50%) after identifying the size of the firm in equilibrium.[38] Second, I separate out the license fee paid to the regulator, lc^F, which represents a pure transfer. (The government charged the entrant $4m per year to operate its network when it did enter.) Third, I separate out the cost of rural tower investments. In urban areas, towers tend to be capacity constrained so that the number of towers scales with call volumes. However, in rural areas, remote towers tend not to be capacity constrained; they scale instead with coverage. For subscribers who primarily use urban towers ($L_i = urban$), I compute incremental costs including the cost of towers. For subscribers who primarily use rural towers ($L_i = rural$), I compute these separately.

[37] Because this study is confidential, I am unable to report the cost estimates.

[38] Because the incumbent's fixed cost is constant across counterfactuals, only the entrant's fixed cost is relevant for evaluating the welfare gains from competition.

I infer the annualized cost of building and operating a rural tower, K_{rural}, from RURA (2011), a study commissioned to set the regulated prices of infrastructure sharing based on cost data from operators.[39]

(See Supplemental Appendix for more details. In a robustness check, I find that given these cost estimates, the monopolist's chosen prices are profit maximizing in the absence of competition.)

6. Simulation

Assumptions. To make simulation tractable, I impose several restrictions. These restrictions are feasible competition rules that could be imposed by the regulator, so that my results will represent a lower bound of the possible welfare gains under more general competition rules.

Operators cannot charge different prices for on- and off-net calls ($p_t^{F,G} \equiv p_t^{F,G'}$). If alternately, both firms offered low on-net charges and high off-net charges, the number of equilibria proliferates: there may be one equilibrium where all consumers subscribe to the entrant, and another where all subscribe to the incumbent. I do not have enough information to discipline the selection of equilibria under those conditions. While a rule to restrict off-net prices 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)).

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

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

operators to connect with others on different networks. Given that I restrict off-network pricing, there is less reason for consumers to hold multiple accounts. For simplicity I rule out that possibility.[40]

At most one switch. To ease computation, I allow individuals to switch operators at most once.

Firm strategy space. I allow firms to set price paths as a multiple of the initial monopolist price path: $\mathbf{p}^F \in \psi \cdot \mathbf{p}^{monopoly}$, where ψ is chosen from a grid.

During the period I study, the government imposed coverage requirements on the incumbent; Bjorkegren (2018) finds that these requirements resulted in the building of roughly 11% of the rural towers active by 2009. Had investment been less profitable, this requirement could have ceased to be viable. My main simulations hold fixed the incumbent's rollout plan and set the entrant's rollout plan to mimic its plans when it did enter (mimicking the incumbent's rollout in urban areas but not covering rural areas; these plans correspond to the coverage maps in Figure 3).[41] I then compute the incumbent's incentives to adjust its investments in response to entry. In the Supplemental Appendix I also consider the equilibria in prices and coverage that would result if the coverage requirement were lifted.

Simulation algorithm. I simulate equilibria $\mathbf{\Gamma}(\boldsymbol{\eta}, \boldsymbol{f}, \tilde{T})$ in two nested steps.

Firm choices. I assume that firms know the communication graph, and consumers' types (η_i^0, η_i^1) up to the estimate I measure (which is either an upper or lower bound), and anticipate whether consumers will coordinate on a high or low network adoption partial equilibrium.

I consider a grid of potential regulator and firm choices (interconnection terms, and price and rollout paths: $\{(\boldsymbol{f}, \mathbf{p}^0, \mathbf{p}^1, \mathbf{z}^0, \mathbf{z}^1 | \boldsymbol{\eta}^0, \boldsymbol{\eta}^1)\}$). I identify an ε-equilibrium on this grid by allowing each firm to iteratively best respond to each other's strategy:

[40]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.

[41]Operator C's global Annual Report in 2010 suggests an urban focus: 'urban centers currently represent the significant majority of the addressable population and we believe that the right approach to reaching more rural areas is increasingly to share network infrastructure with other operators.' Tower sharing in Rwanda was limited until it was mandated by the regulator in 2011.

conditioning on the decision of $-F$, firm F selects $\mathbf{p}^F$ and $\mathbf{z}^F$ to maximize profits through $\tilde{T}$, anticipating how consumers will adopt and use phones. This grid of prices approximates a continuous surface; to ease the computational burden, I first find an equilibrium on a coarse grid, and then iteratively refine the grid near that equilibrium.[42] Best responses can sometimes cycle locally around a small neighborhood; I terminate the algorithm once neither firm would profit more than $\varepsilon = \$2m$ by deviating. If the algorithm discovers multiple ε-equilibria, I report the one for which any profitable deviation is smallest. (See Appendix A for the implementation of the algorithm.)

Consumer choices. Conditional on firm and government choices, I compute a network adoption partial equilibrium $(\mathbf{x}, \mathbf{a})$ using a two step iterated best response method. I bound equilibria by exploiting their lattice structure: i's optimal adoption date x_i is weakly monotonic in his type $\boldsymbol{\eta}_i$, and his contact's adoption date x_j, and coverage $\phi_j^{a_j}$.[43]

In the monopoly case, or when one firm is weakly better for all consumers, equilibria can be bounded simply.[44] The lower bound of the equilibrium with lowest possible adoption, $\underline{\Gamma}$, can be identified by setting each individual's type $\boldsymbol{\eta}_i$ to its lower bound, and initializing the best response algorithm with a complete delay of adoption ($x_i^0 = \bar{T}$) with the operator with worst coverage. The upper bound of the highest possible equilibrium, $\bar{\Gamma}$, can be identified by setting each individual's type to its upper bound, and initial choice to adopt immediately ($x_i^0 = 0$) with the operator with best coverage.

However, when firms are differentiated in two dimensions, the lattice structure can bend. j's choice of operator affects both his adoption date (x_j) and coverage ($\phi_j^{a_j}$), which can have diverging effects on the rest of the network. An individual who switches to a lower priced operator may adopt earlier but have worse coverage;

[42] I start with a grid spaced in increments of 20 percent of the monopoly price, then reduce to 10, and 5. Because I trace out a large set of conditions $\boldsymbol{f}$ and $\tilde{T}$ that induce equilibria in different parts of the grid, I end up evaluating most of the grid finely (see normal form game boards in Appendix and Supplemental Appendix).

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

[44] As in Bjorkegren (2018); see pseudocode in Appendix Section A.

this may make the network more desirable for some contacts and less desirable for others. I compute approximate bounds with a two step method. First, I compute the *quasi*equilibrium that would result from combining the most (least) attractive envelope of coverage and prices offered by the two firms, which is monotonic and represents an upper (lower) bound. Second, I start from that quasiequilibrium to compute the adoption equilibrium in the actual prices and coverage.

On occasion, there remain slight nonmonotonicities which result in a cycle; if a cycle is small, I end the algorithm and consider the result an approximate equilibrium.[45] In a bounding exercise in the Supplemental Appendix, I find that the impact of these nonmonotonicities is small.[46]

Computing a single partial equilibrium takes about 15 hours on a supercomputer, so that computing the roughly 1,000 partial equilibria used in this paper takes approximately 625 supercomputer days.[47]

Dark network. If part of the dark network would have become activated prior to $\tilde{T}$, my approach will underestimate demand. I thus evaluate whether equilibrium prices and coverage would induce the dark network to become active before $\tilde{T}$.

A node that adopted after T at baseline will adopt prior to $\tilde{T}$ in a counterfactual only if the network provides more value before $\tilde{T}$ than it did at baseline at T, based on the adoption condition in Equation 5. A conservative bound, $\tilde{T}^{conservative}(\mathbf{p}, \boldsymbol{\phi})$, can be obtained by shortening the horizon until calling prices, handset prices, coverage, and adoption lie within the conditions observed in sample. However, even if usage prices were lower, handset prices would remain a barrier to adoption for most of the network. I exploit the relationship between usage and handset prices by modeling the adoption of dark nodes, using data from a later survey. Based on this model I

[45] If fewer than 40 nodes are shifted for at least 10 iterations.

[46] My approximate equilibria are bounded by the lattice of equilibria that result when consumers have naïve beliefs about their contacts' coverage (everyone believes that others have the coverage of the incumbent, or the entrant).

[47] To improve computational performance, I reoptimize nodes in parallel, with a synchronized record of all consumers' current choices. A given node is reoptimized only if its conditions or neighbors have changed (analogous to a breadth first search). I use secure computation nodes each with 340GB of RAM and 20 processors, housed at Brown University.

form tighter bounds, $\tilde{T}^{structural}(\mathbf{p}, \boldsymbol{\phi})$, which I use for my primary results.[48] Details are described in Appendix B. In the Supplemental Appendix I also report results through different horizons.

7. Monopoly Benchmarks

Before simulating a competitive equilibrium, I demonstrate how a monopoly model can diagnose how competition may affect the network. I hold fixed individuals' operator choices ($a_{it} \equiv 0$), and trace the impact of prices on welfare, and how the revenue from building rural towers is distributed across the network. These diagnostics can be computed under fewer assumptions about an eventual competitor. For simplicity, I report results under the full horizon of the data (2005-May 2009=T).

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

Lowering prices has large welfare benefits. Anticipating that competition may induce the incumbent to lower prices, I simulate the equilibria that would result if the monopoly were to charge the price that was eventually charged after Operator C entered in 2010 (see Figure 2): an immediate drop in calling prices of 77%. I assume the firm holds this nominal price constant, and expands coverage as in the baseline. I compute first the proximal effect: allowing subscribers to individually reoptimize their usage and adoption holding fixed the adoption of others; and then any additional network effects as the impact of these decisions ripple through the network. This price reduction would have lowered firm and government revenues, and due also to the cost of operating a larger network, substantially reduced firm profits. However, it would have generated huge utility benefits, more than doubling the surplus accruing to consumers. On net, social welfare would have increased by \$277m (low equilibrium) or \$272m (high), which corresponds with 1.6-1.7% of GDP or 8-9% of official development aid over this time period. Since results through T do not include benefits to the dark network, this is likely to represent a lower bound.

[48]This bound will not factor in dark links between observed nodes in my sample that may become active if prices were lower; the conservative bound will.

Most of the welfare improvement comes from proximal effects; 11-19% comes from network ripple effects. Next I consider whether splitting the network could affect investment.

Investment in rural towers generates network spillovers. I estimate the scope for competition to affect investment by decomposing the revenue generated by the construction of rural towers.

Urban areas tend to be more lucrative, and thus profitable to serve even in the presence of competition (population densities are high and operating costs are lower). On the other hand, rural areas may be profitable to serve only if one also has a monopoly over urban areas. If market share in urban areas is split between competitors, two forces lower the returns on investing in a rural tower. First, if firms are not able to charge different prices to rural and urban areas, price pressure in the urban area can lower the revenue earned from rural calls. Second, some of the revenue will spill into the competing network.

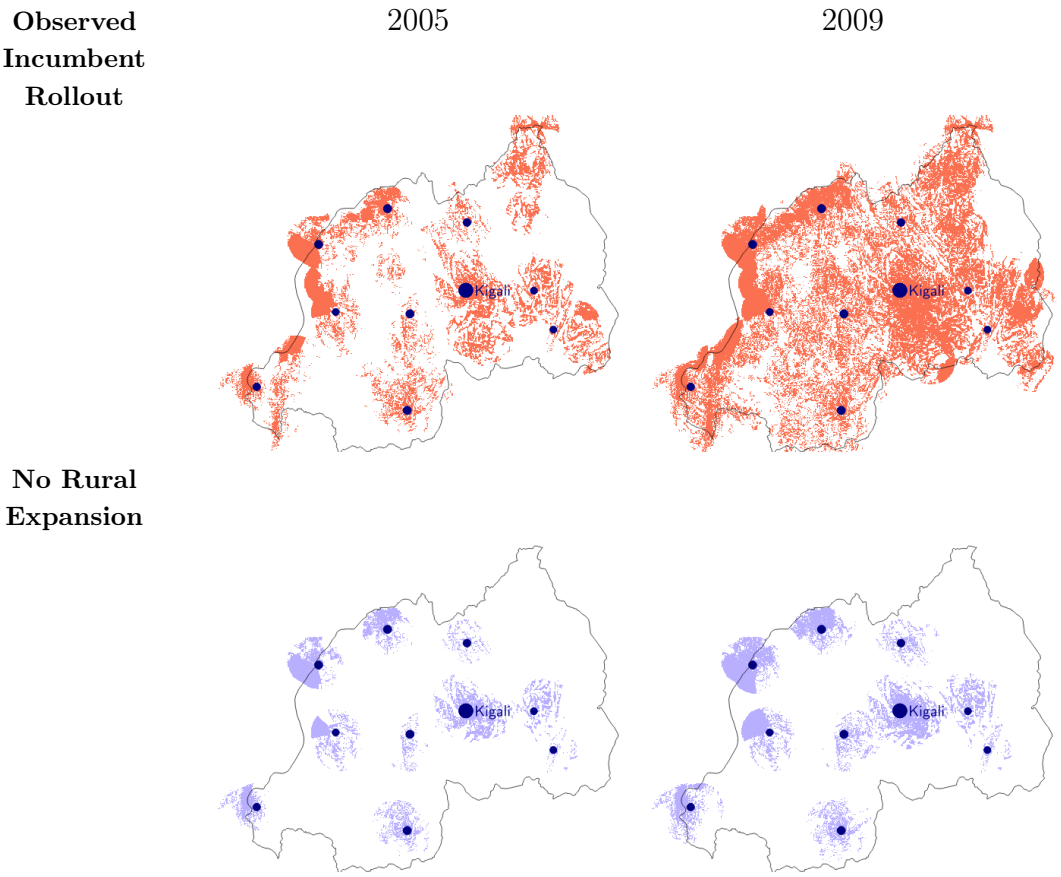
I simulate the effects of building full baseline coverage relative to a counterfactual where only urban towers are built (see Figure 3 for coverage maps). I impose the relevant rollout plan, compute corresponding coverage, allow each consumer to adjust their adoption and calling behavior, and compute resulting equilibrium revenues and utility. I compute first the proximal effect, and then any additional network ripple effects. Since this counterfactual makes the network less attractive, these results will be unaffected by the dark network.

First, I simulate the impact of removing the full rural expansion, holding prices fixed at the monopoly level. As shown in Table 3, while only rural areas received improved coverage, rural-rural links generated only 28% (24%) of revenue. 31% (29%) of revenue came from links between rural and urban areas, and 44% (48%) came from increased calling along urban-urban links. If the network were split, the incumbent would internalize only a fraction of these urban components of the incremental revenue.

I further decompose urban-urban revenue into two parts:

Proximal benefits account for the majority of urban-urban revenue (92% or 75%): some urban consumers make calls from rural areas and thus directly benefit from rural coverage (which would be factored into their coverage measure ϕ_{it}^a). Because

FIGURE 3. Rollout Plans



these consumers would select an operator based on prices, urban coverage, and rural coverage, they would create an incentive for the operator to compete on the quality of rural coverage.

Spillover benefits account for the remainder (8% or 25%): these can result from even consumers who have no desire to call or use rural coverage. These benefits accrue to the interior of the urban network, so would only partially be internalized if that network were split. Standard interconnection charges at the boundary of the networks would not help the incumbent internalize this revenue.

While the rural expansion was profitable at monopoly prices, if the monopoly were forced to reduce prices to the eventual competitive price, incentives to build out the entire rural network are substantially lower (and negative), as shown in the final rows of Table 3.

These simulations suggest that competition has the potential for large welfare impacts but may impact investment. The next section discusses assumptions needed to simulate competition. Section 9 presents results under competition.

8. Extension to Competition

This section evaluates how sufficiently the model estimated in a contested monopoly environment captures behavior under competition. The model imposes constraints on how operators compete, and how consumers respond. 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) are stable upon the introduction of competition.

To evaluate these assumptions I use two kinds of evidence. First, since Rwanda eventually did admit a viable competitor, I use my original consumer choice survey, other surveys, and official statistics after that competitor's entry in 2009. Second, I report evidence from other African countries that had competitive markets during this time. (For more details see Supplemental Appendix section on Operator Differentiators.)

What margins might operators compete on? The model captures competition on coverage and price levels (which may include network effects related to price and coverage); here I consider other potential margins of competition.

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 additional competition entered in Rwanda.[49] The entrant's plans were 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.

Quality. Several call quality measures are regulated under the terms of each operator's license, and quality tests by the regulator suggest little difference between the operators.

[49]With the exception that several years later once smartphones had gained popularity, Operator D specialized in data plans.

TABLE 3. Benchmark Monopoly Simulations (million $, January 2005-May 2009)

	Consumer Surplus	**Gov. Revenue**	**Firm Profits**	**Firm Revenue**				
					By Connection			
	All links	All links	All links	All links	Rural-Rural	Rural-Urban	Urban-Rural	Urban-Urban
Baseline	**[244, 270]**	**[65, 73]**	**[122, 140]**	**[165, 187]**	**[30, 33]**	**[17, 18]**	**[24, 28]**	**[95, 108]**
Impact:								
Charge eventual competitive price	**330, 338**	**-2, -4**	**-51, -62**	**-20, -31**	**-4, -5**	**-4, -5**	**-1, -4**	**-11, -18**
... only proximal effect	288, 316	-7, -9	-58, -67	-32, -39	-5, -6	-5, -6	-3, -5	-18, -22
... additional ripple effects	42, 22	5, 4	7, 5	12, 8	2, 2	1, 1	2, 1	7, 4
No rural expansion	**-81, -92**	**-11, -14**	**-19, -27**	**-32, -42**	**-9, -10**	**-4, -4**	**-6. -8**	**-14, -20**
... only proximal effect	-77, -83	-10, -11	-17, -21	-30, -35	-8, -9	-4, -4	-6, -7	-12, -15
... additional ripple effects	-3, -8	-1, -2	-2, -6	-2, -7	-0, -1	-0, -0	-0, -1	-1, -5
Charge eventual competitive price and no rural expansion	**198, 217**	**-10, -11**	**-56, -66**	**-42, -49**	**-10, -10**	**-7, -7**	**-5, -7**	**-20, -25**
... only proximal effect	155, 200	-14, -14	-62, -69	-53, -55	-10, -11	-7, -8	-7, -8	-28, -28
... additional ripple effects	43, 17	4, 3	7, 3	12, 6	1, 1	0, 0	2, 1	8, 4

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 2).

9. The Effects of Competition

This section presents the results of simulations with competition. The entrant and incumbent simultaneously submit pricing plans, and consumers choose adoption dates, operators, and usage. I compute results up to horizon December 2008= $\tilde{T}^{structural}(0.2 \cdot \mathbf{p}^{monopoly}, \boldsymbol{\phi}^{monopoly})$, prior to when the dark network would become active given equilibrium outcomes, by the model in Appendix B. Firms are not required to share tower infrastructure. I first fix the incumbent's coverage at the government mandated level, and then consider whether it would have incentives to deviate. (In the Supplemental Appendix I also consider equilibria in pricing and incumbent coverage.) Profit measures here omit fixed costs and license fees; I report those separately.

Competition does not develop without government intervention. First, I allow the incumbent to dictate the terms of interconnection (f_{ij}), as is the case with most emerging network goods. Prior to the pricing game, the incumbent selects from a menu of interconnection rates ranging from \$0.00 to \$0.43 per minute. I then compute the resulting equilibrium prices and outcomes. When given the option, the incumbent will set interconnection rate to the highest value: \$0.43. The incumbent continues to charge the monopoly price, and the entrant charges 80% of the monopoly price.[50] I report strategic interactions in normal form in Tables A1 and A2; outcomes do not differ substantially from the monopoly case, as shown in Table 4. This mimics observed the outcomes in many emerging network goods, where one firm is dominant and interconnection does not arise (Katz and Shapiro, 1985).

[50]The entrant is obliged to connect to the incumbent's network, and because of the regulatory restriction that operators charge the same prices for on- and off-net calls, it cannot separately pass through the high cost of interconnection. As a result, the entrant has little advantage to drawing away customers: it pays higher than cost to interconnect with the incumbent's network (as a result, the incumbent earns a higher profit than under monopoly; it now effectively can price discriminate between urban and rural consumers, where rural consumers are willing to pay more for improved coverage).

If the firms coordinated to select an interconnection rate to maximize joint profits, they would select the same high interconnection rate of $0.43 which stalls competition, with outcomes in Table 4. This is reminiscent of theoretical results that suggest that if firms select the interconnection rate, they may use it as an instrument of collusion to sustain high prices (Armstrong, 1998; Laffont et al., 1998).

Adding a competitor under regulated interconnection can dramatically lower prices. If interconnection terms are set to the recommended level presented to the regulator (PwC, 2011), $f_{ij} = \$0.07$, the entrant gains more by drawing away customers. In equilibrium, it attracts only a small market share, but still induces a substantial effect on price and consumer welfare. The entrant would set prices to 35% of the monopoly level, and the incumbent would reduce prices to 45% of the monopoly level, charging a premium for its better quality network. Tables A3 and A4 show the resulting normal form games. Outcomes are shown in Table 4, and the price series is shown in Figure 2. At this scale of operation, the entrant incurs a fixed cost of $6.23m (lower) or $7.57m (upper) of operating over this horizon.

This policy change would have had an enormous impact on welfare. Over the horizon from 2005-2008, at baseline the monopoly provided a social surplus of $334m (lower) or $386m (upper), corresponding with 2-3% of Rwanda's GDP over the same time period. Adding a competitor under this interconnection rate would increase net social welfare by $200m (lower) or $208m (upper), equivalent to 1.4% of GDP or 6-7% of official development aid in Rwanda over the same period.

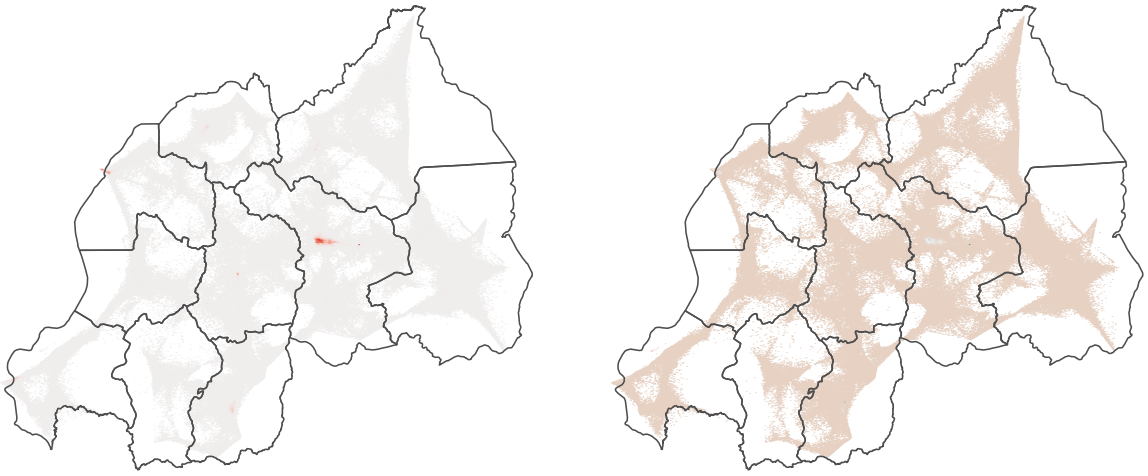
These results do not include a license fee, which represents an additional transfer from the firms to the government.[51]

In this equilibrium, the entrant earns slightly negative profits. This suggests that sustaining this market structure may require subsidizing the entrant on the order of $1m (0.5% of the total welfare generated), or the promise of additional future profits as the network grows. (In 2018, this entrant merged with what was left of the ineffective competitor, returning the market from a triopoly to a duopoly.)

Figure 4 shows the geographic impact of revenue from adding a competitor: the entrant captures revenue in urban centers but pays out interconnection charges for

[51]Competition could reduce these revenues, if it reduces the fee it is feasible to charge the incumbent.

FIGURE 4. Geographical Revenue Impact of Adding a Competitor



(a) Incumbent (b) Entrant

Blue represents gain; red loss.

calls to rural areas; the incumbent loses revenue in the urban network. Table A5 breaks down heterogeneity in the impact on consumer surplus: most of the benefits go to urban consumers who have two appealing networks to select from; but proportionally most gains accrue to new subscribers and rural subscribers who benefit from the incumbent's price reductions.

Increasing competition can increase incentives to invest in rural towers. I next consider whether the incumbent would alter investment in rural towers in response to competition. While determining the exact towers under a profit maximizing rollout is computationally infeasible, I simulate suggestive counterfactuals, where the incumbent may trim back marginal, low revenue towers.

I first rank each tower z by a proxy of how desirable it was for the firm to build: the empirical revenue of the transactions they transmitted ($\bar{R}_z$: 'average direct baseline revenue'). This provides a rough gauge of the desirability of a tower. I propose several cutoffs n and compute the progression of coverage omitting this set of rural towers ($\mathbf{z}_{(n)} = \{z \in \mathbf{z}_{full} | \bar{R}_z > \bar{R}_{(n)}$ or z is urban$\}$, where $\bar{R}_{(n)}$ is the nth order statistic of $\bar{R}$ for rural towers). Given each counterfactual rollout plan (see Appendix Figure A1), I compute each individual's time series of coverage $\phi_{it}(\mathbf{z}_{(n)})$, the resulting link utilities and durations, and then simulate a new network adoption partial equilibrium.

TABLE 4. Competitive Outcomes under Incumbent Coverage Obligation

Policy			Outcomes (January 2005-December 2008)							
	Inter-connect f_{ij}	Switch. Cost s	Prices $\frac{\mathbf{p}^0}{\mathbf{p}^{mono}}$	Prices $\frac{\mathbf{p}^1}{\mathbf{p}^{mono}}$	Incumbent Revenue	Incumbent Profit	Entrant Revenue	Entrant Profit	Gov. Revenue	Consumer Surplus
	$/min	$			$m	$m	$m	$m	$m	$m
Baseline: Contested Monopoly	-	-	1.00, 1.00	-	[141, 164]	[108, 126]	[0, 0]	[0, 0]	[58, 66]	[168, 194]
With additional competitor...					**Impact:**					
Entering January 2005										
Interconnection rate										
...incumbent profit maximizing	0.43	36	1.00, 1.00	0.80, 0.80	-13, -3	+14, +28	+8, -3	+7, -5	-1, -2	+8, +11
...initial proposed level (RURA, 2006)	0.09	36	0.50, 0.45	0.45, 0.35	-4, -29	-22, -43	+4, +13	-1, -1	+2, -1	+215, +261
...**revised** glide path start (PwC, 2011)	0.07	36	0.45, 0.45	0.35, 0.35	-23, -33	-38, -47	+11, +17	-0, +3	-1, -1	+245, +261
...revised glide path end (PwC, 2011)	0.04	36	0.40, 0.40	0.30, 0.30	-37, -50	-53, -65	+16, +24	+4, +9	-3, -4	+271, +293
...bill and keep	0.00	36	0.35, 0.35	0.25, 0.25	-54, -72	-72, -88	+26, +34	+12, +18	-5, -7	+309, +325
...asymmetric	0.07 entrant 0.06 incumbent	36	0.45, 0.45	0.35, 0.35	-22, -32	-37, -46	+10, +16	-1, +2	-1, -1	+245, +261
	0.07 entrant 0.04 incumbent	36	0.50, 0.45	0.40, 0.35	-15, -30	-28, -44	+11, +14	0, 0	+1, -1	+221, +261
Interconnection rate **revised** + number portability	0.07	19	0.45, 0.45	0.35, 0.35	-26, -37	-40, -50	+14, +20	+1, +5	-1, -2	+246, +262

In outcome cells, first number is outcome in low equilibrium; second in high. Profits omit fixed costs of operation and license fees.

The change in coverage has an immediate effect on calls: lower coverage increases the hassle cost of placing a call, reducing durations and the utility from calling. Consumers who obtain less utility from calling may also change their operators, or adoption decision, which can cause even consumers who were not directly affected by the change in coverage to change their adoption decisions.

My main results consider deviations from the full equilibrium where the coverage requirement is enforced. I decompose incentives to invest in Table 5, by market structure and interconnection rate. I first simulate adoption partial equilibria where tower investments are removed, and then measure the effect of adding those investments in two stages: first, if consumers can change adoption dates and usage but not operators, and if consumers can also change operators (thus capturing incentives for operators to differentiate).

I evaluate the returns to building out two components of the rollout plan: the 10 lowest revenue rural towers, which were unprofitable under monopoly (Bjorkegren, 2018), and the 50 lowest revenue rural towers, which together were profitable under monopoly.[52] The social return on both of these investments was positive; and increases under competition as these towers see more use, as shown in the last column of Table 5.

I next decompose the private incentives to build these towers, across the columns of Table 5. The net effect of competition policy on investment arises from three forces, decomposed for the 50 tower case below for the government recommended interconnection rate of \$0.07/minute:

1. Competition lowers overall revenues. Because price discrimination is limited, when the incumbent faces competition in the urban market, it lowers prices across the whole network. As a result, each second of talk time generates less revenue. Under monopoly, investing in towers 1-50 generated a total of \$2.57m (lower equilibrium) or \$2.46m (upper) of revenue. However, under competition it generated net revenue \$1.92m combined between the two operators.

[52]One could alternately difference these to report the incentives to build towers 10-50, however that comparison introduces additional noise.

2. Competition splits the revenue generated by rural towers... Under competition, not only is total revenue lower; it is now split with another firm. As a result, some benefits of investment spill into the competitor's network. To see this more clearly, consider the outcomes that result when consumers can adjust adoption and usage but not operator ('fixing operator').

2a. ...some revenue accrues at the boundary of the competing network. The investment increases calls from the entrant's network to the incumbent's network, shown in the entrant's off-net column. Holding fixed operator choices, under an interconnection rate of \$0.07/minute, 15% of the revenue from the incumbent's investment in the 50 lowest revenue towers accrues to the border with the entrant's network. These spillovers can partially be recouped with interconnection fees: 10% of total revenue is given back under an interconnection fee of \$0.07/minute.[53]

2b. ...some revenue accrues to the interior of the competing network. 0.4% (lower) or 1% (upper) of the revenue generated by the incumbent's investment results from spillovers in the interior of the entrant's network–shown in the entrant's on-net column. Since interconnection fees are incurred only at the boundaries of the two networks, they do not adjust for these internal spillovers. The magnitude of these internal spillovers will depend on the shape of the entrant's network, as well as the degree of network spillovers: they require the entrant's network to be both porous to adoption spillovers, and sufficiently deep that spillovers reach beyond the border. In this case, the entrant's network is relatively small, and these interior spillovers are also relatively small.

On net, effects 1 and 2 lower the return on investment, so that if operator choices were held fixed, the private return on investment decreases, and is negative for either investment.

3. A business stealing effect increases the incentive to differentiate quality. However, the bulk of revenues generated by the investment under competition arise from a

[53]Note that theoretically, there can be cases where competition *increases* revenues from this channel: if operators are sufficiently differentiated that the entrant attracts consumers who would not have adopted under the incumbent, and interconnection fees are large enough. However, in this case, the entrant offers an inferior service that is not sufficiently differentiated.

business stealing motive. Although the networks are interconnected, each firm offers its own set of towers. The effect of this competitive differentiator is observed when consumers are allowed to change their choice of operator (see rows 'plus operator choice'). Because the investment is valued by subscribers who otherwise would select the entrant's network, it induces many of them to switch to the incumbent. This business stealing effect dwarfs the network effects foregone by the incumbent and internalized by the entrant. Altogether, building additional rural towers tends to reduce the entrant's revenues and profits.

With this business stealing effect, the private returns of investing in these rural towers becomes positive, and is larger than the returns under monopoly under the government recommended interconnection rate of \$0.07/minute. However, the balance of these forces depends on the interconnection rate–if the government implemented an interconnection rate of zero ('bill and keep'), competition would lower incentives to build out this part of the network—see the rows in Table 5.

The balance of these forces–and thus, the effect of competition on incentives to invest–will also depend on how preferences interact with the network. Consider an alternate case where consumers did not travel, so that rural consumers valued only rural coverage, and urban consumers valued only urban coverage. Then, the incumbent may be the only option for rural consumers, but urban consumers would not switch operators based on rural coverage. In that case there would no business stealing effect, and competition would tend to lower incentives to invest in towers.

I find similar results if the incumbent were not bound by the government coverage requirement. In a separate exercise in the Supplemental Appendix, I simulate the full equilibria in prices and incumbent coverage without that constraint. In the monopoly case, Bjorkegren (2018) finds the incumbent would only build the 10 lowest revenue towers if required to do so; I find that with an additional competitor, it would build these towers regardless.

The monopoly benchmark simulations presented in Section 7 foreshadow that the business stealing effect is likely to be large here: a large portion of revenue generated by rural towers comes from urban consumers who value and use rural coverage.

The interconnection rate acts as a dial on the level of competition. Figure 5 shows equilibrium outcomes as a function of the interconnection rate (shown decreasing with the x-axis) for rates near the government recommended rate.[54] Adding a competitor under high interconnection rates results in outcomes similar to monopoly. As the interconnection rate is decreased, equilibrium prices decline, incumbent's profits decline, entrant's profits increase, and consumer surplus increases. I compute the effect on incentives to invest for a subset of reasonable interconnection rates from the government recommended rate down to zero. Incentives to build the 50 lowest revenue rural towers decline as the interconnection rate is lowered and the market becomes more competitive.

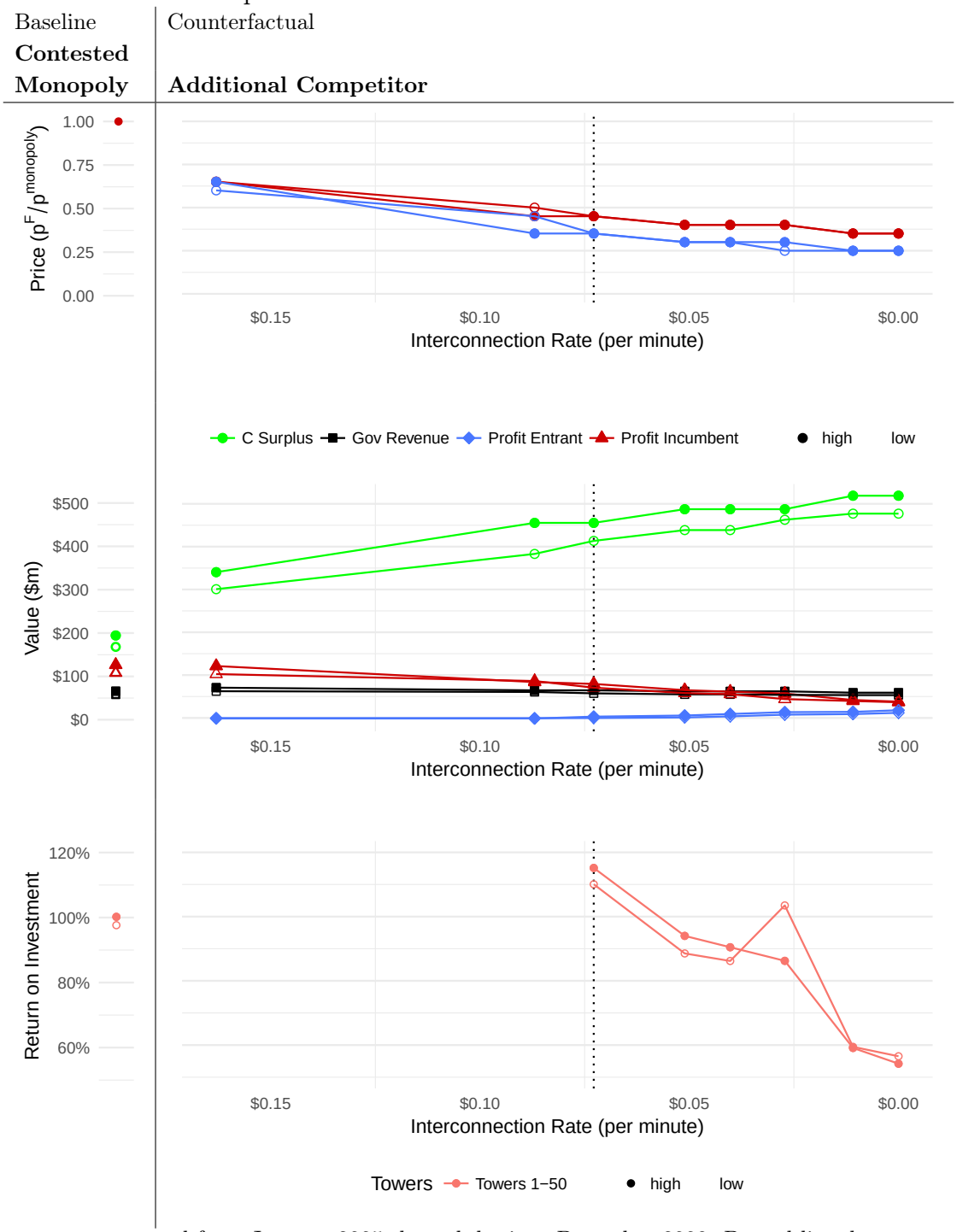
Number portability increases the level of competition. 31% of Rwandans state that they would have switched operators if they could keep their phone number (Stork and Stork, 2008). A common lever over switching costs is to allow consumers to transfer their phone numbers when switching operators.[55] In 2013, 25% of developing markets had introduced number portability and 15% were planning to do so in the future (GSMA, 2013). However, there are concerns that forcing number portability before a market is mature may reduce investment. Rwanda initially planned to introduce portability when mobile operators reached combined 60% market penetration, but as of this writing has yet to do so.

I simulate the effect of introducing number portability, in Table 4, by reducing the cost of switching operators from \$36.09 to \$18.51 (based on my consumer survey estimates; see Supplemental Appendix). This results in more consumers using the entrant, which tends to raise entrant profits at the expense of incumbent profits; it results in a small boost in consumer surplus. I find little heterogeneity in impact between initial and later subscribers (see Appendix Table A5): some later subscribers take advantage of low switching costs to switch to the incumbent after its coverage improves.

[54]There are some interconnection rates in this range that do not lead to an ε-equilibrium for this grid resolution and $\varepsilon \leq$\$2m. I omit these from the plot.

[55]There are similar policy options in other markets. For example, Google criticized Facebook for making it difficult to export lists of friends, thus making it more difficult to switch from Facebook to the nascent Google+ social network.

FIGURE 5. Equilibrium Results as Function of Interconnection Rate



Outcomes computed from January 2005 through horizon December 2008. Dotted line denotes implemented interconnection rate (PwC, 2011). Filled marks denote high equilibrium and open marks denote low equilibrium. In top two plots, red represents incumbent and blue entrant. Bottom plot shows the incumbent's return on investment for the 50 lowest revenue towers.

TABLE 5. Return on Tower Investments under Different Competition Policies

	Equilibrium		**Impact of Investment**							**ROI**	
	Prices		Incumbent			Interconnect	Entrant				
	Incumb. $\frac{p^0}{p^{mono}}$	Entrant $\frac{p^1}{p^{mono}}$	Costs	Revenue		Fees	Revenue		Costs		
				On-net	Off-net calls	←	Off-net calls	On-net		Private	Social
			$m	$m	$m	$m	$m	$m	$m		
Impact of incumbent building towers 1-50											
Contested monopoly	**1.00, 1.00**	-	**1.30, 1.23**	**2.57, 2.46**	-	-	-	-	-	**0.98, 1.00**	**6.64, 6.49**
With competitor, interconnection $0.07/min	**0.45, 0.45**	**0.35, 0.35**	**2.70, 2.79**	**7.85, 8.27**	**-2.54, -2.70**	**0.37, 0.44**	**-1.65, -1.65**	**-1.74, -2.00**	**-1.68, -1.80**	**1.10, 1.15**	**7.85, 8.13**
...fixing operator			1.11, 1.08	0.84, 0.77	0.04, 0.04	0.10, 0.09	0.15, 0.14	0.004, 0.01	0.05, 0.05	-0.12, -0.16	5.86, 5.92
...plus operator choice			1.59, 1.71	7.02, 7.49	-2.59, -2.73	0.27, 0.35	-1.80, -1.78	-1.75, -2.01	-1.74, -1.85	-	-
With competitor, interconnection $0	**0.35, 0.35**	**0.25, 0.25**	**2.85, 3.01**	**6.60, 6.97**	**-2.14, -2.32**	**0, 0**	**-1.13, -0.89**	**-1.53, -1.97**	**-1.84, -2.04**	**0.57, 0.54**	**7.94, 8.21**
...fixing operator			*1.11, 1.08*	*0.84, 0.77*	*0.04, 0.04*	*0.10, 0.09*	*0.15, 0.14*	*0.004, 0.01*	*0.05, 0.05*	*-0.12, -0.16*	*5.86, 5.92*
...plus operator choice			*1.59, 1.71*	*7.02, 7.49*	*-2.59, -2.73*	*0.27, 0.35*	*-1.80, -1.78*	*-1.75, -2.01*	*-1.74, -1.85*	-	-
Impact of incumbent building towers 1-10											
Contested monopoly	**1.00, 1.00**	-	**0.14, 0.14**	**0.05, 0.07**	-	-	-	-	-	**-0.61, -0.50**	**0.63, 0.87**
With competitor, interconnection $0.07/min	**0.45, 0.45**	**0.35, 0.35**	**0.22, 0.22**	**0.46, 0.48**	**-0.16, -0.16**	**-0.02, -0.02**	**-0.15, -0.15**	**-0.07, -0.07**	**-0.09, -0.10**	**0.31, 0.32**	**1.33, 1.37**
...fixing operator			0.14, 0.13	0.03, 0.02	0.001, 0.0009	0.005, 0.01	0.01, 0.01	0.0001, 0.00006	0.002, 0.002	-0.76, -0.80	0.97, 0.80
...plus operator choice			0.08, 0.09	0.44, 0.45	-0.16, -0.16	-0.02, -0.02	-0.15, -0.16	-0.07, -0.07	-0.10, -0.10	-	-
With competitor, interconnection $0	**0.35, 0.35**	**0.25, 0.25**	**0.22, 0.23**	**0.37, 0.39**	**-0.13, -0.13**	**0, 0**	**-0.1, -0.1**	**-0.06, -0.06**	**-0.1, -0.1**	**0.09, 0.13**	**1.36, 1.57**
...fixing operator			*0.14, 0.13*	*0.03, 0.02*	*0.001, 0.0009*	*0.005, 0.01*	*0.01, 0.01*	*0.0001, 0.00006*	*0.002, 0.002*	*-0.76, -0.80*	*0.97, 0.80*
...plus operator choice			*0.08, 0.09*	*0.44, 0.45*	*-0.16, -0.16*	*-0.02, -0.02*	*-0.15, -0.16*	*-0.07, -0.07*	*-0.10, -0.10*	-	-

In outcome cells, first number is outcome in low equilibrium; second in high. Outcomes computed from January 2005 through horizon December 2008. When holding operator choices fixed, consumers who initially switched operators are allowed to change their adoption date for the initial operator but maintain the same switch date. On-net revenues include revenue from extra fees. Interconnect fees represent net payment from entrant to incumbent. Social ROI represents consumer surplus, government revenue, and firm profit, relative to firm costs.

Delaying entry reduces the impact of competition. I consider allowing the competitor to enter on February 2009. I restrict subscribers to only select the incumbent before the entry date ($a_{it} \equiv 0$ for $t < t_{entry}$), or either after that date ($a_{it} \in \{0, 1\}$ for $t \geq t_{entry}$). Outcomes are shown in the bottom of Table 4. This is similar to the baseline case, where the Rwandan government did eventually allow in the entrant (Operator C) at the end of 2009.

Asymmetric interconnection rates give regulators finer control. I also consider asymmetric interconnection rates. Given that interconnection rates accrue only at the border of a network, a regulator may allow a larger network to charge a higher rate to offset spillovers that would otherwise accrue to its interior. (Alternately, the regulator could tilt favor towards a smaller network by allowing it discounted access to the larger network.) I consider outcomes under interconnection rates that favor the incumbent in Table 4: these shift profits from entrant to the incumbent.

Robustness.

Dark Network. 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. (It would infeasible to observe the full network after the Rwandan market became competitive, because that would require linking rich network data across all competitors.) Because competition may make it more attractive to join the network, the omitted, or 'dark', portion of the network could affect results if the horizon is long enough that these individuals would have adopted. The results reported in this section consider the horizon through December 2008; this period would be unaffected by dark nodes, under the assumptions of a structural model of their behavior (see Appendix B). However, results in that horizon could still be affected by dark links between illuminated nodes, which would become active under lower prices. In the Supplemental Appendix I also consider shorter horizons. Holding coverage fixed, I find that equilibrium prices are comparable or lower, and welfare effects are comparable or larger under shorter horizons. Conditional on prices, any omission of dark nodes or links would lead to underestimating the incentives to invest in rural towers

under competition.[56] This suggests that my results may underestimate the benefits of competition in the presence of dark nodes.[57]

10. Conclusion

Societies are grappling with an increasing number of industries characterized by network effects. This paper develops a method to simulate the effects of competition policy in a network industry. I demonstrate how data from an incumbent monopoly can be used to estimate the effects of a variety of competition policies. My method captures how changes ripple throughout networks and across network boundaries, and can thus decompose how the policy environment affects incentives to invest. In addition to the policies demonstrated here, this method can also estimate effect of splitting up an incumbent, under arbitrary splits of customers and assets (while such a policy was not under consideration in my context, it is under consideration in others).

I focus my approach on an industry of particular importance to developing societies: mobile phone networks provide the infrastructure for an increasing array of vital services, including communication and increasingly payments and banking. I find that competition in the Rwandan mobile phone industry has a large scope to affect welfare. I find that policies to increase competition have mixed effects on incentives to invest: they split the revenue generated by rural towers, but this effect is mostly dominated by increased returns from differentiating quality. While I focus on the primary investments in this network, in rural towers, network firms have a menu of potential investments which would be differentially affected by competition. Competition will tend to make investments that induce a marginal customer to switch more attractive, and investments that induce dispersed network spillovers less attractive. It is thus likely to affect the technological direction of a market.

[56] Any nodes or links that I omit would benefit consumers, pushing adoption forward, and would represent additional revenue.

[57] If the firms set lower prices, that could reduce the revenue obtained from an investment, but a regulator could impose a price floor to obtain price and investment outcomes as least as beneficial as I observe here.

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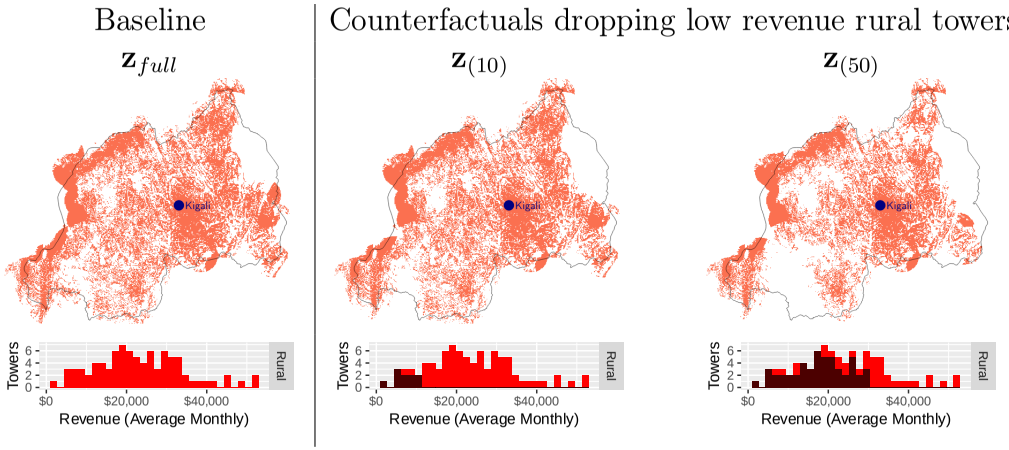
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FIGURE A1. Menu of Tower Investments for Incumbent



Coverage as of May 2009.

	10pct	15pct	20pct	25pct	30pct	35pct	40pct	45pct	50pct	55pct	60pct	65pct	70pct	75pct	80pct	85pct	90pct	95pct	Full
10pct	-25, **1**																		
15pct	101, -109	-4, **1**																	
20pct	142, -140	110, -99	15, **1**																
25pct	176, -171	158, -138	109, -81	32, **0**															
30pct	**184**, -179	180, -157	164, -129	114, -70	43, **0**														
35pct	181, -180	**188**, -165	176, -137	154, -106	99, -45	55, **0**													
40pct	164, -167	181, -162	**183**, -146	171, -119	146, -87	107, -41	67, **0**												
45pct	142, -148	164, -149	177, -143	**173**, -123	158, -97	150, -80	114, -38	78, **0**											
50pct	121, -129		155, -124	167, -121	161, -101	159, -87	154, -73	116, -31	87, **0**										
55pct			139, -111	148, -105	**161**, -105	**161**, -91	159, -78	143, -56	104, -13	90, **0**									
60pct			117, -92	134, -94	141, -89	161, -94	**167**, -87	149, -61	133, -41	97, -2	95, **0**								
65pct			103, -79	114, -76	128, -78	141, -78	162, -86	**156**, -70	133, -41	123, -25	103, -1	102, **0**							
70pct	77, -92				110, -62	127, -66	141, -68	152, -70	**142**, -53	135, -37	117, -14	107, -1	105, **0**						
75pct						109, -51	125, -55	131, -53	142, -56	**140**, -45	124, -23	**119**, -14	108, -1	107, **-0**					
80pct			73, -55		84, -40	95, -39	108, -41	117, -41	123, -40	135, -45	**129**, -32	116, -14	114, -8	109, -0	108, **0**				
85pct													114, -9	109, -2	**109**, -0	**109, -0**			
90pct	52, -72				67, -26		82, -18		95, -18		110, -21		**117**, -16	108, -2	104, **4**	108, -0	**108**, -0		
Full	47, -69	47, -50	48, -34		52, -14	56, -6	65, -4		71, 2	78, 2	85, -2	95, -6	100, -8	**110**, -14	105, -4	97, **7**	102, 4	**106**, 0	**106**, 0

Incumbent actions in rows; entrant in columns. Cells represent incumbent and entrant profits, in million USD.
Best responses are bolded. Underlined cell represents a Nash Equilibrium.

TABLE A1. Competitive Interaction: Interconnection $0.43 Switching Cost $36 Low Equilibrium -200812 (50pct dark)

	10pct	15pct	20pct	25pct	30pct	35pct	40pct	45pct	50pct	55pct	60pct	65pct	70pct	75pct	80pct	85pct	90pct	95pct	Full
10pct	-24, **1**																		
15pct	115, -123	-2, **1**																	
20pct	155, -152	125, -111	18, **1**																
25pct	186, -181	172, -150	133, -100	37, **0**															
30pct	**196**, -190	192, -166	188, -148	139, -89	54, **0**														
35pct	189, -187	**200**, -175	195, -152	191, -135	143, -79	67, **-0**													
40pct	173, -175	194, -172	**203**, -161	199, -140	191, -121	145, -67	77, **-0**												
45pct			195, -156	**202**, -144	**199**, -126	190, -107	129, -45	85, **-0**											
50pct	129, -136		171, -136	192, -138	198, -126	**196**, -112	170, -83	133, -39	96, **-0**										
55pct			153, -121	168, -118	192, -125	193, -111	179, -89	173, -76	138, -35	105, **-0**									
60pct			128, -98	149, -102	168, -104	187, -108	**182**, -94	177, -79	175, -69	143, -32	114, **-1**								
65pct					149, -88	164, -89	171, -89	**179**, -83	177, -71	169, -55	147, -28	120, **-0**							
70pct	85, -99				124, -66	143, -72	150, -71	172, -80	**179**, -75	177, -64	167, -46	134, -14	122, **-1**						
75pct					108, -52	121, -52	134, -58	149, -61	172, -72	**180**, -69	176, -57	160, -39	126, -4	123, **-1**					
80pct			83, -60		96, -41	105, -37	116, -42	132, -47	148, -51	172, -65	**180**, -63	163, -42	149, -28	127, -2	126, **-1**				
85pct						94, -28	100, -27	115, -32	131, -37	147, -43	171, -58	**164**, -46	150, -29	**147**, -23	129, -2	**128, -1**			
90pct	59, -78				77, -25	84, -21	88, -17	100, -19	115, -24	131, -30	145, -36	159, -45	**153**, -35	144, -22	**138**, -14	127, **-1**	**127**, -1		
95pct							79, -10	87, -8	98, -8		129, -22		148, -35	143, -26	135, -14	125, **-0**	126, -1		
Full	54, -75	55, -56	58, -40		61, -13	64, -5	70, -3		86, **1**	97, -1	113, -8	119, -13	128, -19	138, -26	134, -18	128, -7	124, 0	**125**, -0	**125**, -0

Incumbent actions in rows; entrant in columns. Cells represent incumbent and entrant profits, in million USD.
Best responses are bolded. Underlined cell represents a Nash Equilibrium.

TABLE A2. Competitive Interaction: Interconnection $0.43 Switching Cost $36 High Equilibrium -200812 (50pct dark)

	10pct	15pct	20pct	25pct	30pct	35pct	40pct	45pct	50pct	55pct	60pct	65pct	70pct	75pct	80pct	85pct	90pct	95pct	Full
10pct	-22, **-2**																		
15pct	11, -18	-1, **-1**																	
20pct	27, -26	25, -13	17, **-1**																
25pct	38, -33	39, -20	37, -9	34, **-1**															
30pct	**42**, -37	46, -23	49, -14	49, -5	45, **-1**														
35pct	41, -40	**48**, -25	**52**, -14	56, -8	57, -4	57, **-1**													
40pct	37, -40	45, -26	52, -15	**58**, -7	**63**, -4	68, -2	69, **-1**												
45pct	33, -38	40, -25	48, -14	56, -6	62, -1	**71, -0**	77, -1	79, -1											
50pct	28, -36		41, -11	49, -3	58, 2	68, **4**	**77**, 3	**85**, 1	88, -1										
55pct			36, -8	42, 0	51, 5	62, 9	72, **9**	82, 5	**90**, 1	92, -1									
60pct			30, -5	37, 3	43, 10	54, 13	66, **14**	76, 12	86, 7	**96**, -0	97, -1								
65pct			26, -3	31, 6	37, 12	45, 18	56, **20**	68, 18	78, 14	91, 7	**102**, -0	103, -1							
70pct	17, -32				31, 16	38, 22	47, **26**	57, 25	68, 21	81, 17	95, 8	**106**, -0	107, -1						
75pct						32, 26	39, 31	47, **32**	58, 28	71, 24	83, 18	96, 8	**107**, -0	108, -1					
80pct			17, 1		23, 21	27, 29	32, 35	39, **37**	46, 36	58, 32	71, 26	85, 18	99, 8	**109**, -0	**110**, -1				
85pct													87, **18**	101, 7	109, -0	**110**, -1			
90pct	9, -29				17, 24		23, 41		32, **45**		46, 43		72, 28	87, 18	102, 6	108, -0	**110**, -1		
Full	6, -29	7, -10	9, 5		11, 27	14, 36	16, 44		22, 51	25, **54**	30, 53	36, 52	45, 47	57, 39	72, 29	87, 17	100, 6	**106**, -0	**107**, -1

Incumbent actions in rows; entrant in columns. Cells represent incumbent and entrant profits, in million USD.
Best responses are bolded. Underlined cell represents a Nash Equilibrium.

TABLE A3. Competitive Interaction: Interconnection $0.07 Switching Cost $36 Low Equilibrium -200812 (50pct dark)

	10pct	15pct	20pct	25pct	30pct	35pct	40pct	45pct	50pct	55pct	60pct	65pct	70pct	75pct	80pct	85pct	90pct	95pct	Full
10pct	-22, **-1**																		
15pct	13, -20	0, **-1**																	
20pct	30, -27	28, -15	20, **-1**																
25pct	41, -35	43, -21	42, -10	39, **-2**															
30pct	**45**, -39	49, -24	54, -15	55, -5	55, **-2**														
35pct	44, -42	**51**, -26	**57**, -14	64, -8	66, -2	69, **-2**													
40pct	40, -42	48, -27	57, -15	**64**, -5	**72**, -2	77, **1**	78, -2												
45pct			52, -13	62, -4	71, 2	**79**, **3**	**84**, 0	86, -2											
50pct	31, -38		45, -10	55, -1	66, 6	76, **8**	84, 4	**93**, 1	97, -2										
55pct			39, -7	47, 4	58, 9	69, **13**	79, 11	90, 7	**101**, 2	106, -2									
60pct			33, -4	40, 7	49, 15	60, **19**	71, 16	83, 15	96, 10	**108**, 3	**115**, -2								
65pct					42, 19	50, **25**	60, 22	74, 22	87, 19	102, 12	114, 4	**122**, -2							
70pct	19, -33				35, 24	42, 29	50, 29	62, **29**	77, 27	91, 22	107, 13	118, 2	**123**, -2						
75pct					30, 27	35, 34	42, 34	51, **37**	64, 36	79, 32	94, 26	107, 14	121, 1	124, -2					
80pct			20, 3		26, 29	30, 37	36, 38	43, 43	53, **44**	66, 41	82, 35	95, 26	109, 13	**125**, 0	127, -2				
85pct						26, 39	30, 42	36, 47	43, 50	53, **51**	67, 46	81, 36	96, 25	111, 13	**127**, -0	**129**, -2			
90pct	11, -30				20, 33	23, 41	26, 45	30, 51	37, 55	44, **57**	54, 56	67, 47	81, 36	97, 25	112, 11	126, -0	**128**, -2		
95pct							22, 47	26, 54	30, 59		44, **63**		66, 47	81, 36	97, 24	116, 8	125, -0		
Full	8, -30	10, -10	11, 7		14, 34	16, 44	19, 49		26, 62	30, 66	37, **68**	43, 64	52, 57	65, 47	81, 36	97, 23	116, 8	**125**, -0	**126**, -2

Incumbent actions in rows; entrant in columns. Cells represent incumbent and entrant profits, in million USD.
Best responses are bolded. Underlined cell represents a Nash Equilibrium.

TABLE A4. Competitive Interaction: Interconnection $0.07 Switching Cost $36 High Equilibrium -200812 (50pct dark)

Appendix A. Simulation Algorithms

The simulation algorithm can be described in three nested steps. For monopoly simulations, operator choices are held fixed at $a = 0$.

Adoption Iterated Best Response Algorithm.

Require: firm price paths $\mathbf{p}$ and coverage paths ϕ

Require: candidate adoption path $\mathbf{x}^0$ and operators $\mathbf{a}^0$

$k \leftarrow 0$

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, $\tilde{t} \leftarrow \bar{T}$

        $\mathbf{a}^*_a \leftarrow [\underbrace{a \quad a \quad \cdots \quad a}_{\tilde{t} \text{ elements}} \underbrace{(1-a) \quad (1-a) \quad \cdots \quad (1-a)}_{\bar{T}-\tilde{t} \text{ elements}}]$

        solve $t^*_a \leftarrow \arg\max_s E_t U_i^{\mathbf{a}^*_a, s}(\mathbf{a}^k_{G_i}, \mathbf{x}^k_{G_i})$

        $u^*_a \leftarrow E_t U_i^{\mathbf{a}^*_a, t^*_a}(\mathbf{a}^k_{G_i}, \mathbf{x}^k_{G_i})$

      end for

      $a^* \leftarrow \arg\max_a u^*_a$

      if $t = t^*_{a^*}$ **then**

        $x_i^{k+1} \leftarrow t$

        $\mathbf{a}_i^{k+1} \leftarrow \mathbf{a}^*_{a^*}$

        break

      end if

    end for

  end for

  $k \leftarrow k + 1$

until $\mathbf{x}^k = \mathbf{x}^{k-1}$ or fewer than 40 nodes shifted in each of the last 10 iterations

return iterated best response path $\mathbf{x}^k$ and operators $\mathbf{a}^k$

Network Adoption Partial Equilibrium.

Require: firm price paths $\mathbf{p}$ and coverage paths ϕ

TABLE A5. Impact of Competition: Heterogeneity

Policy			Outcomes (January 2005-December 2008)				
			Consumer Surplus				
	Inter-connect f_{ij}	Switch. Cost s	All	Urban Subscribers	Rural Subscribers	Initial Subscribers	Noninitial Subscribers
	\$/min	\$	\$m	\$m	\$m	\$m	\$m
Baseline: Contested Monopoly	-	-	[168, 194]	[140, 163]	[29, 32]	[95, 99]	[73, 95]
Impact of adding competitor...							
...**revised** glide path start (PwC, 2011)	0.07	36	245, 261	199, 213	46, 48	97, 98	149, 164
Interconnection rate **revised** + number portability	0.07	19	246, 262	199, 213	46, 48	97, 98	149, 164
N			1,503,670	671,285	832,385	421,173	1,082,497

In outcome cells, first number is outcome in low equilibrium; second in high.

Require: bound $\in \{\text{lower}, \text{upper}\}$

if bound = upper **then**
  compute adoption iterated best response quasiequilibrium $\tilde{\mathbf{a}}, \tilde{\mathbf{x}}$ given lower envelope of firm price paths $\mathbf{p}$ and upper envelope of coverage paths $\boldsymbol{\phi}(\mathbf{z})$ starting from $\tilde{\mathbf{a}}_0 = \mathbf{0}, \tilde{\mathbf{x}}_0 = \mathbf{0}$
  compute adoption iterated best response equilibrium $\mathbf{a}, \mathbf{x}$ given firm price paths $\mathbf{p}$ and coverage paths $\boldsymbol{\phi}(\mathbf{z})$ starting from $\mathbf{a}_0 = \mathbf{0}, \mathbf{x}_0 = \tilde{\mathbf{x}}$
else if bound = lower **then**
  compute adoption iterated best response quasiequilibrium $\tilde{\mathbf{a}}, \tilde{\mathbf{x}}$ given upper envelope of firm price paths $\mathbf{p}$ and lower envelope of coverage paths $\boldsymbol{\phi}(\mathbf{z})$ starting from $\tilde{\mathbf{a}}_0 = \mathbf{1}, \tilde{\mathbf{x}}_0 = \bar{\boldsymbol{T}}$
  compute adoption iterated best response equilibrium $\mathbf{a}, \mathbf{x}$ given firm price paths $\mathbf{p}$ and coverage paths $\boldsymbol{\phi}(\mathbf{z})$ starting from $\mathbf{a}_0 = \mathbf{1}, \mathbf{x}_0 = \tilde{\mathbf{x}}$
end if
return consumer partial equilibrium path $\mathbf{x}$ and operators $\mathbf{a}$

Full Equilibrium. The full equilibrium adaptively refines the grid near the equilibrium identified on successively less coarse grids. My main simulations impose the government coverage requirement $\mathbf{z}_0 = \mathbf{z}_{full}$; in the Supplemental Appendix I consider equilibria in prices and coverage.[58]

Require: interconnection terms $\mathbf{f}$ and tolerance ε

$\underline{\mathrm{r}}_0, \underline{\mathrm{r}}_1 \leftarrow 0.10$
$\bar{r}_0, \bar{r}_1 \leftarrow 1.00$
$k \leftarrow 0$
$\mathbf{p}_0^0, \mathbf{p}_1^0 \leftarrow \mathbf{p}^{monopoly}$
for Δ in $\{0.2, 0.1, 0.05\}$ **do**
  repeat
    for firm $F = 0$ to 1 **do**
      $\mathbf{p}_F^{k+1}, \mathbf{z}_F^{k+1} \leftarrow \arg\max_{\mathbf{p}_F, \mathbf{z}_F} \pi_F(\{\mathbf{p}_F, \mathbf{p}_{-F}^k\}, \{\mathbf{z}_F, \boldsymbol{z}_{-F}^k\}, \mathbf{a}, \mathbf{x}, \boldsymbol{f})$
      s.t. $\mathbf{p}_F \in \{\underline{\mathrm{r}}_F, \underline{\mathrm{r}}_F + \Delta, \underline{\mathrm{r}}_F + 2\Delta, ..., \bar{r}_F\} \cdot \mathbf{p}^{monopoly}$

[58] For those simulations, to reduce the computational burden, I first refine the grid around an equilibrium in prices, and then allow for deviations in prices and coverage around that equilibrium, as described in the algorithm below.

s.t. $\mathbf{z}_0 \in \{\mathbf{z}_{full}, \mathbf{z}_{(10)}, \mathbf{z}_{(50)}\}$ if $\Delta = 0.05$ else $\mathbf{z}_0 = \mathbf{z}_{full}$

s.t. $\mathbf{z}_1 = \mathbf{z}_{\text{no rural}}$

s.t. $\mathbf{a}, \mathbf{x}$ are a network adoption partial equilibrium given firm price paths $\mathbf{p}$ and coverage paths $\boldsymbol{\phi}(\mathbf{z})$

end for

until $\mathbf{p}_0^{k+1} = \mathbf{p}_0^k$ and $\mathbf{p}_1^{k+1} = \mathbf{p}_1^k$ and $\mathbf{z}_0^k = \mathbf{z}_0^{k+1}$ or reaches a cycle with a deviation that earns profits below ε. If so, break at least profitable deviation.

$\bar{r}_0 \leftarrow \frac{\mathbf{p}_0^k}{\mathbf{p}^{monopoly}} + \Delta$

$\bar{r}_1 \leftarrow \frac{\mathbf{p}_1^k}{\mathbf{p}^{monopoly}} + \Delta$

$\underline{\mathrm{r}}_0 \leftarrow \frac{\mathbf{p}_0^k}{\mathbf{p}^{monopoly}} - \Delta$

$\underline{\mathrm{r}}_1 \leftarrow \frac{\mathbf{p}_1^k}{\mathbf{p}^{monopoly}} - \Delta$

end for

return firm price paths $\mathbf{p}$ and rollout plans $\mathbf{z}$, and consumer equilibrium path $\mathbf{x}^k$ and operators $\mathbf{a}^k$

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

Rwanda's complete communication graph includes active nodes that have purchased phones and active links along which calls were placed, as well as latent nodes that could potentially purchase phones and latent links along which calls could potentially be placed if conditions were different. It would be prohibitively costly to gather data on this complete network: it would require a network census of Rwanda that estimated the demand of every *potential* communication link. I use transaction data to observe the active network ($G^T \subseteq \bar{G}$), up to T =May 2009 under monopoly provision. I do not observe links in the latent or dark network. In this section I develop bounds on the behavior of the dark part of the network.

Estimates of an outcome through horizon $\tilde{T}$ may be biased if either:

(1) There are any nodes i which are not observed in my data (they adopted later under monopoly conditions: $x_i(\mathbf{p}^{monopoly}, \boldsymbol{\phi}(\mathbf{z}^{monopoly}), \mathbf{x}_{-i}^{monopoly}, \mathbf{a}_{-i} = \mathbf{0}, \boldsymbol{\eta}) > T$), who would adopt before $\tilde{T}$ in a counterfactual ($x_i(\mathbf{p}, \boldsymbol{\phi}(\mathbf{z}), \mathbf{x}_{-i}, \mathbf{a}_{-i}, \boldsymbol{\eta}) \leq \tilde{T}$).

(2) There are any links ij which are not observed in my data (there were no calls placed before T under monopoly conditions), which would have become active before $\tilde{T}$ in a counterfactual.

I evaluate results under three approaches.

Full horizon. This approach reports results up to horizon T. Because these results do not include the behavior of the dark part of the network, they may be biased. If latent nodes and links became active, holding prices fixed that would increase incentives to invest in rural towers, because the same cost would generate revenue from more subscribers. Thus, holding prices fixed, such an approach would underestimate the returns to investment under competition. However, the effect on prices is ambiguous.

Conservative approach. The most conservative bound reports results only up until the month before the dark network would have seen preferable adoption and usage conditions. This approach is akin to a counterfactual of speeding up a film using fast forward: if the original film is 5 minutes long, you may run out of tape at 3 minutes: the film could not tell you what happens after those 3 minutes.

I select a limit $\tilde{T}^{conservative}(\mathbf{p}, \boldsymbol{\phi})$ so that the network does not yield more utility under counterfactual prices $\mathbf{p}$ and coverage $\boldsymbol{\phi}$ than it did at baseline at T:

$$\min_{t \leq \tilde{T}^{conservative}(\mathbf{p},\boldsymbol{\phi})} \mathbf{p} \geq \min_{t \leq T} \mathbf{p}_t^{monopoly}$$

$$\max_{t \leq \tilde{T}^{conservative}(\mathbf{p},\boldsymbol{\phi})} \boldsymbol{\phi}_t \leq \max_{t \leq T} \boldsymbol{\phi}(\mathbf{z}^{monopoly})_t$$

I do not similarly bound η_1: some individuals in the dark network may have an idiosyncratic preference for the entrant. However, my survey includes individuals in the dark network and finds that idiosyncratic preferences are very slight, and mostly favor the incumbent.

Then under the condition that $\eta_{i1} \leq \eta_{i0}$, each dark node i and link ij faced conditions at least as attractive at T in the baseline as it does in the counterfactual before $\tilde{T}^{conservative}(\mathbf{p}, \boldsymbol{\phi})$. Since in the baseline, dark nodes chose to wait until after T to adopt, in a counterfactual they would choose to wait until after this period. Likewise, any dark links would not become active before this period. As a result, outcomes reported up until $\tilde{T}^{conservative}(\mathbf{p}, \boldsymbol{\phi})$ will be unaffected by the omission of the dark network for prices $\mathbf{p}$ and coverage $\boldsymbol{\phi}$.

While this approach is valid, it is conservative and does not fully exploit the variation I observe. The next approach develops a tighter bound using the structural connection between handset and usage prices.

Structural approximate approach. This approach reports up to the month $\tilde{T}^{structural}(\mathbf{p}, \boldsymbol{\phi})$ before the dark network would have preferable adoption conditions, modeling the utility of the dark network using later survey data. Under the assumptions of the model, before $\tilde{T}^{structural}(\mathbf{p}, \boldsymbol{\phi})$ dark nodes and any links to dark nodes will not affect results. (Dark links between observed nodes could potentially affect results; I discuss later here.)

Although competition affects usage prices, it does not affect handset prices, which are offered by a perfectly competitive independent market. The price of a handset represented a major barrier to adoption during this period, and declined dramatically from 2005 to 2011. A subscriber who waited for a large decline in handset prices would be unlikely to subscribe much earlier for a relatively small decline in usage prices. This approach exploits the model to relate the variation in handset prices that was observed under monopoly provision to the variation in usage prices that would be observed under competition.

I use a household survey that is representative of mobile phone subscribers in Rwanda in $T_{survey} = 2011$, several years after my data ends ($N = 350$, conducted by the NGO, Research ICT Africa). 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).[59] 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 illustrate the intuition of this approach in Table A6. At the beginning of 2005, an average handset cost $147.73 (quality adjusted index). Individuals who adopted at the beginning of 2011 saved $132.65 by waiting 6 years to adopt, with discounting. In a counterfactual, such an individual would only move forward adoption to the beginning of 2005 if he would have obtained at least $132.65 more in usage utility during those years. However, relative to handset prices, subscribers spend little using their phone,

[59] I assume that individuals that adopted before 2011 still have phones when surveyed in 2011.

TABLE A6. Handset Prices versus Usage

Year	Handset Price Index ($)	Change in Handset Price ($)	For adopters in this year, Mean Airtime Spending Month of Survey in 2011 ($)	Total Number of Mobile Phone Accounts (Regulator)
2005	147.73	-51.05	4.41	138,728
2006	96.68	-34.37	3.39	222,978
2007	62.31	-13.76	4.12	322,561
2008	48.55	-8.66	5.11	554,642
2009	39.88	-3.11	2.81	1,322,637
2010	36.77	-14.14	2.34	2,497,170
2011	22.63	-2.14	2.92	3,548,761

Reported in 2005 US dollars. Handset taxes eliminated July 1. Number of total accounts in Rwanda reported as by the regulator at the beginning each year.

and later subscribers (dark network) subscribers spend less. Individuals who adopted in 2011 spent an average of $2.92 in the month prior to being surveyed. If they had adopted in 2005 and maintained that same level of usage over the next 6 years, that would correspond to total discounted usage of $173.40. However, the mobile phones were much more useful in this later period: as shown in the last column of the table, the network was substantially larger, and coverage was substantially expanded. I next connect this data to my model to evaluate the amount of utility associated with a level of spending on usage, and to approximate changes in the size of network, coverage, and usage prices.

Using survey data, I infer how each individual traded off usage utility against the price of handsets in the baseline environment. This survey lacks the detailed network information I would need to fully model behavior as in the rest of the paper, so I 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; this will represent a valid bound of behavior under a competitive environment under the condition $\eta_{i1} \leq \eta_{i0}$. For clarity I omit the choice of operator from notation. I assume that in a counterfactual, any individuals measured in the survey (adopting 2009-2011) would adopt prior to any individuals who waited until after 2011 to adopt (and thus are omitted from the survey).

I evaluate the impact of dark nodes by forming lower bounds on each i's adoption date,

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

under counterfactual calling price sequence $\mathbf{p}$. I use two survey questions to evaluate the choices of dark nodes. 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 $p_{T_{survey}} \cdot \sum_{j \in G_i^{T_{survey}} \cap S_{T_{survey}}} d(\epsilon_{ijT_{survey}}, \mathbf{p}_{T_{survey}}, \phi_{iT_{survey}}, \phi_{jT_{survey}}, \mathbf{a}_{T_{survey}})$.[60]

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 deviations 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, $\underline{\mathrm{u}}_{i,x_i-k}(p_{x_i-k})$ for Equation 10. At month $x_i - K$, i must have believed that waiting to adopt until some month $\tilde{K}$ would be preferable:

$$\bar{\eta}_i^0 \leq \bar{\bar{\eta}}_i^0 = \max_{\tilde{K}>0} \left[\frac{1}{1-\delta^{\tilde{K}}} \left[p_{x_i-K}^{handset} - \delta^{\tilde{K}} E_{x_i-K} p_{x_i-K+\tilde{K}}^{handset} - \sum_{s=0}^{\tilde{K}-1} \delta^s E \underline{\mathrm{u}}_{i,x_i-K+s}(p_{x_i-K+s}) \right] \right]$$

The survey asks how many years ago the handset was purchased, so I consider deviations of $K = 12$ months and allow individuals to select between adopting in January of each year.

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. Then, approximating Equation 3:

$$Eu_{it}(p_t, \boldsymbol{\phi}_t, \boldsymbol{x}) \approx Eu_i^{approx}(p_t, \gamma_t, \boldsymbol{\phi}_t) \coloneqq \gamma_t \cdot |G_i| \cdot Eu_{median}(p_t, (\phi_{it}\phi_{jt})^{median_{ij}})$$

γ_t accounts for growth in the network by scaling the number of contacts by the total number of subscribers on the network at month t.[61] I allow each individual to have a

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

[61] $\gamma_t^{baseline}$ is derived from regulator statistics on mobile subscriptions; see Supplemental Appendix.

different level of usage, scaled by their approximate number of 'links' $|G_i| = \frac{d_{iT_{survey}}}{d^{median}_{T_{survey}}}$ which I infer from the level of spending. Given the levels of usage prices and coverage, the median link would lead to an expected monthly call duration of $d^{median}_{T_{survey}} = 36.1$ seconds at the time of the survey. I allow the utility of each 'link' to vary with calling prices and coverage, tracking the expected monthly call utility of the median link $Eu_{median}(p_t, \boldsymbol{\phi}_t)$.

I use this mapping to derive bounds on usage utility:

$$\underline{u}_{it} \leq Eu_{it}(p_t, \boldsymbol{\phi}_t, \boldsymbol{x}) \leq \bar{u}_{it}$$

where

$$\underline{u}_{it} \coloneqq Eu_i^{approx}(p_t, \gamma_t^{baseline}, \boldsymbol{\phi}_t)$$

$$\bar{u}_{it} \coloneqq Eu_i^{approx}(p_t, \gamma_t^{eq}, \boldsymbol{\phi}_t)$$

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 the optimal choice of x_i decreases in the usage utility and η_i, we can obtain a lower bound of x_i by using the upper bound of both quantities:

$$E_t U_i^x(\mathbf{p}, \boldsymbol{\phi}, \boldsymbol{x}_{G_i}) \leq E_t \bar{U}_i^x(\mathbf{p}, \boldsymbol{\phi}, \boldsymbol{\gamma}^{eq}) = \delta^x \left[\sum_{s \geq x}^{\infty} \delta^{s-x} Eu_i^{approx}(\mathbf{p}_s, \gamma_s^{eq}, \boldsymbol{\phi}_t) - E_t p_x^{handset} + \bar{\bar{\eta}}_i \right]$$

Analogous to Equation 5, a lower bound on i's adoption date is then given by:

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

Then $\gamma_t^{eq} = \sum w_i \cdot 1_{\{\underline{x}_i(\mathbf{p}, \boldsymbol{\gamma}^{eq}) \leq t\}}$, where w_i represents the population weight of each individual.[62] To find an upper bound on the dark network's behavior, 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 $\boldsymbol{\gamma}^{eq}$.

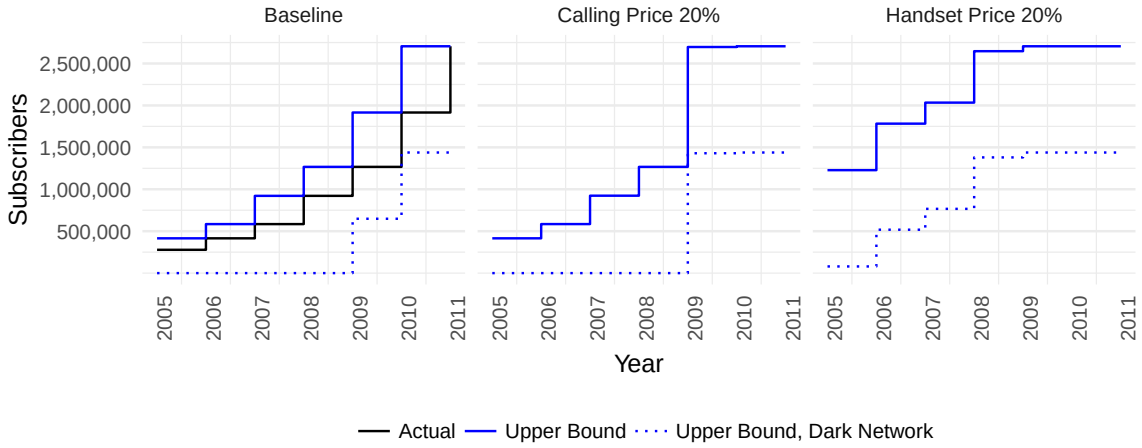
[62]The total number of accounts implied by the survey data during the earlier period is less than the number present in the phone records. My results will be valid as long as in a counterfactual, any nodes omitted from the survey would not adopt prior to those in the survey. (To account for this difference, I multiply survey weights by an adjustment factor, equal to 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: 2.13.)

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

Figure A2 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 calling prices were 20% of the baseline monopoly price series, the first adoptions of the dark network would be in 2009; if handset prices were 20% of the baseline series, the first adoptions would be in 2005.

I then set $\tilde{T}^{structural}(\mathbf{p}, \boldsymbol{\phi})$ to the last month before the first predicted adoptions of the dark network under counterfactual prices $\mathbf{p}$ and coverage $\boldsymbol{\phi}$. Since I consider counterfactuals that weakly decrease coverage, I compute bounds under the monopoly level of coverage. Then, the bounds on $\tilde{T}$ are similar for the range of prices above $0.2 \cdot \mathbf{p}^{monopoly}$; I use that bound for all results. Under the assumptions in this section, dark nodes and links to dark nodes will not affect results prior to $\tilde{T}^{structural}(\mathbf{p}, \boldsymbol{\phi})$. Results may still be affected by latent links between nodes that were active at time: two adopters who did not call each other under monopoly prices may do so under competitive prices. The omission of these links will tend to lower the revenue estimates, and, conditional on prices, lower the estimated returns from investing in towers. I gauge the impact of this omission by comparing results under $\tilde{T}^{structural}(\mathbf{p}, \boldsymbol{\phi})$, which omits these latent links, to those under $\tilde{T}^{conservative}(\mathbf{p}, \boldsymbol{\phi})$, would include the behavior of any latent links and represents a shorter time period, in the Supplemental Appendix.

FIGURE A2. 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.