

Single vs Multiple Standards: A Structural Analysis of the US Wireless Telecommunications Industry

Job market paper

Michela Bonani

CentER

Tilburg University

mail : m.bonani@tilburguniversity.edu

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Abstract

There has been a longstanding debate around whether a single standard is more beneficial than multiple competing standards, because of the ambiguous welfare implications from compatibility. This paper studies the effect of a single technology standard in the U.S. wireless telecommunications market from 2015 to 2018. I develop and estimate a structural model of consumer choice of wireless carriers and coverage investment to quantify the impact of a compatible network on market outcomes and welfare. Using counterfactual simulations, I find that compatibility is the welfare superior policy, regardless of the technology chosen. While the overall producer surplus is higher when moving to uniform wireless networks, whether consumers are better-off depends on the technology standard chosen. Under a Global System for Mobile Communications (GSM) regime, consumer surplus decreases by \$1.7 billion, coverage decreases by 20.01%, and prices increase for two wireless carriers. Under a Code division multiple access (CDMA) compatible network, consumer surplus increases by \$2.2 billion, coverage decreases by 9.78%, and prices fall for all four major carriers.

JEL CLASSIFICATION:

KEYWORDS:

1 Introduction

With regard to public policy towards wireless technology standards, Europe and U.S. followed two very different paths. Whereas the European Commission mandated that all network operators allocated spectrum licenses deploy only one single technology (spectrum regulation), the Federal Communication Commission (FCC) adopted flexible licensing policies regarding wireless standards. Specifically, mobile telephone service carriers have the flexibility to deploy the network technologies they choose. As a result of the market-based approach, different U.S. carriers have chosen to deploy a variety of different technologies with two incompatible technology migration paths: the Global System for Mobile Communications (GSM) and the Code division multiple access standards (CDMA).

The divergent approaches taken to manage the spectrum for wireless voice and data services have generated policy and antitrust debates, because of the ambiguous welfare implications from mandating compatibility. For a given quality of the technologies in a market and a level of investment, switching to a compatible regime gives consumers access to the combined investment of all firms, which may benefit consumers by increasing network externalities (Katz and Shapiro, 1985) and lowering prices. However, benefits to consumers can be offset by a decrease in the firms' investments. Compatibility changes the nature of competition among firms, turning the firms' investments from demand substitutes that steal business from competitors to complements that have positive spillovers among firms. Therefore firms may invest too much under incompatibility because the private gain from business stealing does not contribute to social surplus, while they may invest too little relative to social optimum under compatibility because private incentives do not internalize positive spillovers. Besides, compatibility might require that components be more similar in other respects, thus product differentiation can be reduced under a single standard (Farrell and Saloner, 1985), which in turn might affect the consumer surplus.

Despite the growing theoretical literature on compatibility, the effect of a single standard on welfare is still an open empirical question. This paper develops and estimates a structural model to understand how a compatibility policy affects market outcomes and welfare in the U.S wireless telecommunications industry. This study contributes to our understanding of the telecommunications sector, and to the debate over the intervention of the government with mandated standards when firms invest in incompatible complementary products.

There is a relatively large theoretical literature on compatibility. To a large extent, this literature assumes that compatibility has benefits that make it a socially desirable outcome. This is less obvious in the case of wireless standards. In the case of the telecommunications market, as long as the networks are interconnected¹ and coverage is good, compatibility should not matter. In addition to price, consumers care about the size of the network for which they can place and receive calls. Compatibility will matter when the coverage of the competing network operators differs significantly.

¹Interconnected networks ensure that consumers using different technologies to communicate with each other.

Understanding the market structure of the wireless telecommunications market is critical to understanding how compatibility may affect firms' incentives and consumers' benefits. In the upstream part of this vertical market, firms collaborate to develop the mobile system's technology. The technology is then used as an input to produce intermediate and final goods, such as semiconductors, mobile devices, and wireless equipment. Wireless service carriers buy telecommunication equipment to build wireless networks which provide services downstream. Therefore those firms are the agents deciding upon the technology standards deployed in the networks.

In the wireless industry, the presence of incompatible technology standards does not prevent consumers from benefiting from network effects. In other words, every consumer can communicate with every other consumer, regardless of which technology they are locked into. By compatibility in this industry, I mean the ability of network equipment and wireless terminals to work on other networks. Since the two standards deployed in the wireless networks are incompatible in the sense that the technologies built upon one standard cannot be deployed in the network using the other standard, a lack of compatibility implies higher costs for upstream firms, who have to develop network and terminal equipment based on different technologies. To the extent that these higher costs are reflected in prices, consumers are worse off (Cabral and Salant, 2014). Therefore, in the wireless industry, the main concern for consumers concerning compatibility are prices rather than network effects, and the decrease in the provider's network quality due to lower incentives to investment.

In this paper, I evaluate the impact of compatibility by assessing how the investment in coverage infrastructure and prices set by firms would have changed if the FCC had imposed a single technology standard. First, I develop a structural model of consumers' choice of wireless carriers and firms' coverage investment decisions. The model allows for flexible substitution patterns across firms deploying different standards in their network on the demand side and for endogenous coverage choices by firms on the supply side. I estimate the model using an individual-level dataset of wireless carriers' choices in the U.S. wireless telecommunication market in the period 2015-2018. I use the model and parameter estimates to simulate market outcomes if there had been a single standard deployed in the wireless network. I then compare the status quo to the counterfactual market equilibria under respectively a unified GSM and CDMA network.

Several challenges exist in analyzing how a change to a single standard policy affects outcomes and social welfare. First, there exists little guidance in the empirical literature on the effect of compatibility in oligopolies when firms can adjust prices and product attributes. Second, compatibility changes the nature of competition between firms, turning the firms' investments from demand substitutes, that steal business from rivals, to demand complements, that have positive spillovers into other firms. Since the increase in coverage by a firm affects the coverage available to consumers with a rival provider using the same standard, firms may invest less under a unified network as they can free-ride on the other firms' investments. Therefore, answering this question in the context of the telecommunications market requires a demand model with flexible substitution patterns

between firms deploying different technologies in their networks and within a subset of firms deploying the same technology standard. I define the network available to consumers as the combined coverage infrastructure of a carrier and its rivals deploying the same technology standard. Hence, the model captures the free-riding effects among firms deploying the same technologies in their network. I cast the available coverage infrastructure as a service characteristic in the static discrete-choice framework, following Goolsbee and Petrin (2004). I estimate the demand parameters using a multinomial probit model.

I model wireless carriers as competing in a static oligopoly, in which they set prices and the coverage infrastructure. On the supply side, I treat the coverage investment decision as endogenous and continuous. The model recognizes different investment costs, depending on the standard deployed in the network. The model builds on Berry et al. (1995); Li (2017); Nevo (2000) and the recent literature studying equilibrium outcomes when firms can adjust one or more product attributes (Fan, 2013; Crawford et al., 2019). I estimate the model using the generalized method of moments (GMM). Since I allow the investment decision to be continuous in coverage, I rely on an interactive algorithm to find the equilibrium coverage for each firm. Combining demand parameter estimates and the first-order conditions of the profit function, I recover the marginal costs and the per-unit investment costs under the GSM and the CDMA standard.

Using parameter estimates from the consumer and firm models, I assess the impact of a counterfactual compatibility policy in wireless networks. Specifically, I quantify the effects of a single standard comparing a compatible network deploying the GSM technology and a network using the CDMA technology. I employ an interactive algorithm to find the equilibrium of the firms' simultaneous-move game, under the two single standard regimes. My framework allows firms to adjust both prices and coverages, keeping the per-unit investment costs for GSM and CDMA coverage fixed. I find that firms do have an incentive to cut back by 20.01% and 9.78% of investment on average, respectively under a GSM and a CDMA regime. The reduction in the coverage under compatibility suggests that firms make excess investments when the government allows for competing standards. Surprisingly, the equilibrium prices increase with the GSM standard for two major carriers in this market, but they decrease under CDMA. Though consumer surplus improves by about \$2.2 billion under a CDMA policy, it decreases by about \$1.7 billion under a GSM policy.

Under a compatible network, both a CDMA standard and a GSM standard have higher total welfare. Even though the overall producer surplus is higher when moving to uniform wireless networks, not all firms are better off under a compatible network. The lower profit earned by some firms can explain why the U.S. telecommunications market did not achieve a unified network. These results also might point out a necessary intervention by the government to mandate compatibility. Besides, the gains from compatibility are not symmetric and independent from the technology standard deployed in the market. Whether consumers benefit from compatibility depends on the technology chosen. Two main mechanisms are driving the results of the counterfactual analysis. First, under compatibility consumers lose one dimension of product differentiation and the decrease

in the utility is higher when the GSM technology is the chosen standard. Furthermore, the decline in the GSM coverage investment is not compensated by a decrease in prices, which negatively affects the utility for consumers. My results underline the risks related to the fact that mandating compatibility can trap an industry in an inferior technology (Farrell and Saloner, 1985) and that policymakers should be careful in choosing the mandated technology standard.

The rest of the paper proceeds as follows. Section 2 discusses the evolution of wireless technology standards, the U.S. wireless telecommunications market, and the dataset. Section 3 shows empirical evidence on the free-riding effect between firms deploying the same technologies in their network. Section 4 specifies a model of consumer network provider choice and provider investment in network quality. Section 5 discusses the identification and the estimation procedure. The results of the empirical analysis are discussed in Section 6. Section 7 uses the model estimates to simulate market outcomes and welfare under compatible networks. Section 8 concludes.

Contribution to the literature. This paper contributes to three different streams of literature. The first contribution is to the standard-setting literature and the empirical understanding of the impact of a single standard policy. Previous empirical work on the impact of compatibility has found substantial gains in total welfare and consumer surplus (Ho, 2006; Li, 2017). However, firms’ strategic responses to compatibility may moderate the gains in consumer welfare (Ishii, 2005; Knittel and Stango, 2008, 2011; Lee, 2013). I contribute to this literature by studying the effect of single standards in the wireless telecommunications industry, by accounting for the technological differences of the standards the government mandates. After computing the counterfactual equilibrium, I find that compatibility improves total welfare, regardless of the technology chosen. While firms benefit from moving to uniform wireless networks, whether consumers are better-off depends on the technology standard.

Second, this paper contributes to the literature on the wireless industry. This literature uses discrete choice demand systems to estimate wireless operator incentives in a dynamic optimization setting. These papers include network quality as a component of consumer utility, but only as an exogenous control. For instance, Zhu et al. (2011) and Sinkinson (2014) both study the value of the exclusivity of the iPhone to AT&T and include measures of signal quality. Similarly, Macher et al. (2019) study the substitution and complementarity of fixed and wireless lines and include the total number of the national number of cell sites, locations that house base stations, in their demand system to proxy for improving quality of cell service overall. Björkegren (2019) looks at the Rwandan quasi-monopoly to estimate positive demand externalities among consumers. As he has access to the Rwandan operator’s private data, he also has information about base station location and includes coverage as an endogenous component of utility. Given the complexities of his model, he cannot fully simulate equilibrium coverage provision even for the monopoly but does partial equilibrium counterfactuals about base station location in response to a government program. In contrast to this literature, I model firms playing a series of static games but I treat the quality choice as an endogenous and continuous variable. Moreover, this paper

bridges a gap between these two literature streams by building a framework that allows for a multi-dimensional response in prices and network quality to compatibility in the wireless telecommunication industry.

Third, this paper contributes to the literature studying equilibrium outcomes when firms can adjust one or more product attributes Fan (2013); Crawford et al. (2019), studying how firms adjust prices and investments under different compatibility policies.

2 Industry Background and Data

2.1 The history of wireless standards

The history of standardization policies in the wireless telecommunications industry in the United States started in the early 1980s when the telecommunication regulation authority, the Federal Communication Commission (FCC) approved the Advanced Mobile Phone System (AMPS) as a uniform technology standard to be deployed in the licensed spectrum. Analog systems, also called first-generation (1G) systems, used the allocated radio spectrum in a relatively inefficient way and they supported voice-only calls.

In 1994 the FCC started the licensing process of a new spectrum for digital or Personal Communications Services (PCS), establishing the introduction of digital technologies, 2G and 3G afterwards, to replace analog systems. 2G technology was an improvement over the analog 1G technology: the introduction of digital technologies led to a change in the performance and quality of mobile telecommunications. Moreover, it also allowed operators to offer new data services, such as SMS, call waiting, and caller ID. Compared to its regulation policy in the 80s, the FCC did not mandate a specific standard for the PCS bands: mobile phone carriers were free to choose whatever standard they wished. By the late 1990s, wireless service providers installed two incompatible digital technologies: the Global System for Mobile Communications (GSM) and the Code division multiple access (CDMA) standards.

As the mobile market kept growing, the industry moved toward a third-generation system (3G), which offered vastly improved data transfer capacity, better security, and the support of more advanced data services like multimedia messaging, improved internet browsing, video calling, and GPS navigation. It allowed consumers to use their cell phones in a more data-demanding way. In this context, two competing 3G standards were developed: the UMTS, also named 3GSM, and the CDMA2000.² The UMTS path is for those networks that used GSM for launching 2G. The CDMA2000 path allows 2G CDMA networks to migrate to 3G.

²The UMTS and the CDMA2000 are two competing family of 3G mobile technology standards for sending voice, data, and signaling data between mobile phones and cell sites. They are defined as the mobile cellular systems for networks based on the GSM standard and the CDMA standard respectively. A complete network system includes the radio access network (UMTS Terrestrial Radio Access Network, or UTRAN), the core network (Mobile Application Part, or MAP) and the authentication of users via SIM (subscriber identity module) cards. For details see UMTS standard.

The CDMA2000 was a direct development of the CDMA technology, and therefore it was backwards compatible with its predecessor 2G network, which made the upgrade from 2G to 3G technologies easy and consistent. Instead, the UMTS was an extension in the GSM path, but it used the Wideband Code Division Multiple Access (WCDMA) technology which was built on the CDMA standard.³ In other words, the air interface for UMTS was based on WCDMA which was different from the interfaces GSM employed. Thus 3G UMTS migration required major upgrades to the radio network as new base stations were needed. The additional costs that network operators faced to upgrade the existing systems to the 3G standards, explains in part why UMTS's introduction was delayed in most places. It also explains why there were 2G networks still functioning in the United States during the late 2010s.⁴

Furthermore, in the few places where a UMTS system was introduced, it failed to attract significant numbers of new subscribers. Indeed, from a consumer point of view, since UMTS networks were designed to be compatible with the GSM networks, any 3G mobile phone could still connect to the 2G GSM networks. However customers required new mobile phones in order to be able to access the UMTS networks.

Table 1 describes the main differences between the GSM and the CDMA technologies. On one hand, GSM has a lower data transfer but better coverage, given the fact that it is the mandated standard in most European and Asian countries, allowing consumers to switch their devices between operators easily. On the other hand, the CDMA technology requires more processing power but it has a better data rate. The core technological advantage of the CDMA standard, as compared to GSM, revolved around the concept of packet switching. A CDMA-based call works by breaking up the signal into many different pieces (called packages) and routing these to their destination via different pathways. For mobile phones, the technology allows not just for greater and more reliable call quality, but also better utilization of the expensive data channels. In comparison, the competing GSM standard relied on a less effective underlying technological principle known as circuit switching, which established one fixed link for the duration of a call, thus requiring more bandwidth than packet switching and reducing cost effectiveness.⁵

2.2 The Mobile Phone Market

In the United States, consumers purchase a plan from carriers to provide service on their wireless phones or handsets. Wireless service consists of two components: the mobile voice and the data service. Wireless carriers currently provide an array of mobile voice and data services, ranging from conventional interconnected mobile voice service to text and photo messaging services to high-speed mobile Internet access services provided over mobile wireless broadband networks. As consumer behavior and telephone usage have changed, also due to an

³Though WCDMA does use a direct-sequence CDMA transmission technique like the CDMA2000, WCDMA is not simply a wideband version of CDMA2000. The WCDMA system is a new design and it differs in many aspects from CDMA2000.

⁴See (Leonard, 2009) and (Gandal et al., 2003) for more details on wireless standards.

⁵Wikipedia, Comparison of wireless standards, CDMA, and Leonard (2009)

Table 1
GSM vs CDMA

GSM standard	CDMA standard
SIM specific	Handset specific
Network tower in each cell serves the phones on a area	Physical channel + specific code for each device
Voice and data transmission simultaneously	Not possible
Roaming worldwide	Limited roaming between operators deploying CDMA
Slow data rate	Fast data rate

Source: ETSI website

increase in the number of functionalities that a phone can perform, mobile telephone providers have started to offer mobile voice and data services jointly, and cellphone users have tended to purchase them in bundles.

The handset is essentially a hand-held radio transceiver. When an action is made, the handset sends information to the nearest antenna that services your carrier over that carrier's frequency band of the electromagnetic spectrum. These antennas are part of the carrier's base stations, equipment facilities that reroute the information through the landline telephone system. If the receiver of the call is also on a cell phone, the call will leave the landline network and be rerouted to the nearest base station to the receiver, and the base station will beam the call information to the target.

The locations and the distances of the base stations define the carrier's wireless network. The network set by each provider affects the quality of the mobile voice and data services offered, by affecting the power of the signal transmitted. The power of the signal transmission decreases with distance, so if no carrier's base station is in range, then the signal power between the phone and the base station will be too weak to start a call. Therefore, the quality of the network depends crucially on the ability of the base station to form and maintain transmissions. Even when a consumer is close enough to a base station to initiate a call, there can still be problems since random ambient interference, such as a storm, might overwhelm the signal and disrupt it. This disruption ends the transmission of information, creating a dropped call. Accordingly, carriers are interested in building base stations to make sure their market areas are well covered and dropped calls are kept to a minimum. The more base stations in an area, the more likely a consumer will be in range and the less likely a call would be dropped.

However, base stations are very costly. Aside from the costs of equipment, maintenance, and power, base stations must be mounted on elevated structures. Therefore, a large tower must be built or space on a preexisting tall structure must be rented. Developing and acquiring these locations or sites requires significant regulatory proceedings with local zoning authorities, which can take years. Thus carriers face a trade-off between improv-

ing the quality of their networks and the high investment costs they face to build new base stations. Lastly, this decision is constrained by the geographical composition of a market. For instance, the presence of mountains or lakes affects the locations where carriers can build towers. These factors are exogenous to the firms and they are likely to affect all the carriers investment decisions in coverage homogeneously.

The value of each base station is likely to vary by firm, as network quality depends also on the technology and spectrum available to different firms. In the United States, different firms use different technologies to encode their signals. AT&T and T-Mobile use variants of the GSM standard, in which each call is apportioned a different part of the spectrum of the carrier in that area. CDMA, used by Verizon and Sprint, interweaves calls from all users over the carrier's entire local spectrum. Theoretically, a CDMA signal will travel farther than a GSM signal so a CDMA carrier might need less base station density to yield more quality. In addition to varying across carriers, base station effectiveness likely varies by markets due to idiosyncratic engineering aspects of the different locations. Interference from the mountain or a particular configuration of tall buildings might make a base station less effective than it otherwise would be. Thus it is important for estimation to allow for both variation between firms and also some unobservable component of local market quality.

Aside from the standard path followed by each carrier, the quality of the network depends on the technological generation deployed. Wireless service providers keep upgrading and expanding their existing networks with technologies that enable faster data transfer speeds, which in turn provides better data service to consumers. Notably, firms deploy both 2G and 3G network technologies during the period I focus on. Even though all providers started migrating to 3G technologies in 2005, the presence of 2G networks is justified by the incompatibility of WCDMA network equipment with the GSM network. This limitation is one explanation of why the 3G introduction has been delayed, even if it leads to a better service.

Moreover, wireless carriers offer wireless services primarily using their own network facilities, although coverage areas often are supplemented through roaming agreements. From the consumer point of view, a roaming agreement between two carriers means that when the consumer's phone loses the signal of its wireless provider, it will roam on the partner network. Notably, the consumer accesses the combined network of the carrier and of its partners but under a priority criterion: the carrier's network is the first used by the phone, and when the consumer leaves the coverage area of the provider chosen, the phone will use the roaming network.⁶ Depending on the technologies deployed by each carrier and the incompatibility across technologies, the wireless providers have set agreements with competitors deploying the same technology standards.⁷ Therefore, AT&T

⁶Even though the Commission has taken actions to facilitate roaming arrangements between providers, the conditions defined are subject and specific to each agreement as well as they vary across agreements and providers. For instance, costumers might be subject to a limited amount of MB data to use per month in the roaming network. Moreover, providers can include the price of nationwide roaming services in the plans' monthly fees instead of billing for roaming on a usage basis. For detailed information about roaming between providers see the FCC Seventeenth and Nineteenth Reports.

⁷This depends on the fact that the two competing 3G standards use different frequencies and protocols to work, which does not allow network providers deploying different standards to share their networks. In fact, W-CDMA uses the DS-CDMA channel access method with a pair of 5 MHz wide channels, while the competing CDMA2000 system uses one or more available 1.25 MHz channels for each direction of communication. The conditions for setting roaming agreements changed from 4G LTE technologies

and T-Mobile signed several roaming agreements starting from 2003 which, as a consequence, led to a significant expansion of the GSM network.⁸ On the other hand Sprint signed a roaming agreement with Verizon since they both deploy CDMA technologies and given the Verizon strength of its expansive coverage network.⁹

In addition, spectrum holdings are also a network quality concern in two dimensions. First, the spectrum represents the capacity of information that a base station can support in an area at any one time. So, the capacity measures the amount of traffic, in terms of the number of simultaneous calls and maximum data speed, a network can handle at a given time and depends on the spectrum owned by a provider. A call can be dropped or switched to another base station if spectrum becomes full so a carrier with more spectrum may have less dropped calls. As the number of subscribers increases, providers might need an increase in capacity in order to avoid dropped calls and lower data rates. Capacity is more of an issue when dealing with data, in which firms slow down data transfer to deal with congestion. For the purposes of this analysis, I will abstract from capacity concerns and assume firms hold enough spectrum that have allowed them to invest appropriately in upgrading their base stations to mitigate capacity issues over my sample period.

Second, and potentially more important, different parts of the electromagnetic spectrum have different properties. Frequencies under 1000 MHz propagate farther and therefore are more useful in rural areas. AT&T and Verizon have almost all this spectrum since this was the first spectrum apportioned to firms. Other carriers like Sprint and T-Mobile are late entrants from the mid to late 1990s when most of the low-frequency spectrum had already been distributed. Thus, Sprint and T-Mobile might yield less quality from base stations than their rivals.

2.3 Data

I build a comprehensive repeated cross-section database of wireless service carriers in the United States from 2015 to 2018. The data I use for estimating my model come from several data sources.

Consumer's choice of wireless carriers. The demand is estimated from the Nielsen Consumer Panel dataset¹⁰, a survey that asks approximately 40,000-60,000 U.S. households (not the same every year) about, among other products, their mobile phone-carrier purchase decisions, as well as when and where they make purchases. The dataset reports the handset-carrier bundle chosen, the quantity purchased, the zip code, and consumer demographics. Since I don't observe the carrier, but the handset-carrier pair chosen by each consumer, this can be a source of concern for the estimation of the empirical model. Notably, the choice for a carrier can be driven by the type of cell phone offered with a plan. This limitation is overcome by the fact that smart-

onwards.

⁸For details on the roaming agreements see AT&T and T-Mobile agreement, AT&T, T-Mobile, Timeline Roaming Agreement 2011.

⁹For details on the roaming agreements see Sprint Corporation and Sprint and Verizon Roaming Agreement, as well as the FCC Seventeenth report that can be found at FCC Reports.

¹⁰After submitting a proposal of my project, I was acquiesced to access the Nielsen data, stored and distributed by the Kilts Research Center, Chicago School of Business.

phone operating systems such as the Android and the Apple iOS are available from multiple service providers, permitting consumers to pair their preferred operating systems with various wireless providers. Therefore the decision of the consumers to use one carrier compared to another is unlikely to be affected by the type of phone offered in the plan.¹¹ Even though customers may be able to find the same devices from several different service providers, the promotion and marketing of specific devices may vary across providers. I include these sources of variation across carriers in my model, accounting for unobservable attributes at the firm-market-year level.

Furthermore, consumers in the United States have changed their preferences when choosing cellular voice and data services in the last decades, moving to buy handset services in bundles. Mobile wireless service plans are generally available without bundled contracts, but there are incentives to purchase devices bundled with service plans, and this is still the overwhelming U.S. industry practice, despite recent growth in the prepaid segment.¹²

Demographic data. I use the Nielsen Consumer Panel to retrieve demographic information of consumers. Specifically, I use income¹³, household size, and age since they are especially important for taste variation in choosing wireless providers. Income is likely to affect price sensitivity; household size will proxy for the value of family plans that are very popular options; and age proxies for the affinity for new technology. I use the observed household income levels to construct 4 income groups. To do so, I build the quartiles from the income distribution and I then assign each household to a group depending on the quartile values. Regarding age, the consumer panel reports 9 age categories of the head of the household. Since each category is defined within the same range, I use the mean age from each range as the observed age of consumers.

Besides, I use the US Census website and publicly available databases to collect the estimated total population living in each block. I then use the mapping tables from the Census Bureau to group the blocks at the county and then at the market level.¹⁴

Wireless carrier price and characteristics. There is a wide variety of pricing plans offered by the different mobile wireless service providers that vary along several dimensions, and that may frequently change. It is difficult to identify sources of information that track actual mobile wireless service prices in a comprehensive and consistent manner. One explanation for this complex picture is the large number of possible plans a consumer can choose among.¹⁵

¹¹One major source of concern is the exclusive contract between AT&T and Apple to carry the iPhone. But since the contract expired in 2011 and the sample period is 2015-2018, this is not going to affect the results of the empirical analysis.

¹²Federal Communication Commission, Sixteenth and Seventeenth Reports.

¹³In the Nielsen database, the Income values represent the total household income for the full year that is 2 years prior to the Panel Year.

¹⁴The Census Bureau assign numeric codes, GEOIDs, that uniquely identified all statistical geographic areas for which the Census Bureau tabulates data. GEOIDs are very important for understanding and interpreting geographic and demographic data and their relationship to one another. Data users rely on GEOIDs to join the appropriate demographic data from censuses and surveys to various levels of geography for data analysis, interpretation, and mapping.

¹⁵In reality the number of possible plans is large. A July 31, 2013 article in the Wall Street Journal, "Inside the Phone-Plan Pricing Puzzle", notes there are 750 smartphone plans from the four major carriers.

To measure the price paid by a consumer for its wireless service, I rely on an average price metric reported by the Cellular Telecommunications and Internet Association (CTIA). The CTIA every year publishes an Average Revenue per Reported Unit (ARPU), which is based “upon total revenues divided by the average total reported active units¹⁶ per survey period, divided by the number of months in the survey period” for the four major wireless carriers in the United States. Since the ARPU can be approximated as an annualized monthly bill, I multiply the ARPU of each provider by the number of months in a year, in order to obtain the annual bill paid by a consumer.¹⁷

As an average metric, it has some limitations given the high variation in terms of plan characteristics and pricing for mobile voice and data services. Moreover, the total revenues of each provider, as reported by CTIA, include not only wireless services fees but also usage-related charges, activation charges, vertical services, such as voice mail, and roaming fees paid by consumers. Given the measure of price used and since I don’t observe the plan chosen by the consumers, I assume that each carrier offers only one plan to consumers for an average price, identified by the ARPU. Moreover, since the revenues measured by the CTIA also include the roaming fees paid by consumers to access the network of rivals deploying the same technology standards, the ARPU comprise the average roaming price paid by each consumer.

Regarding the technology standard chosen by each wireless carrier, I use the reports published by the national regulator of telecommunications, the Federal Communication Commission, to define whether each of the 4 major carriers deploys the GSM or the CDMA technologies in its network. AT&T and T-Mobile deployed the GSM standard in their networks, while Verizon and Sprint followed the CDMA path for developing their networks.

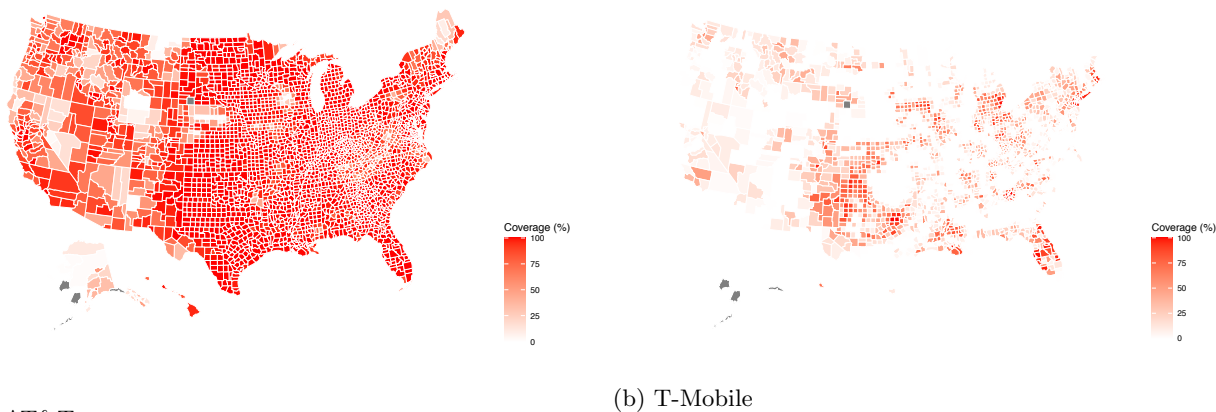
Coverage infrastructure. The coverage is defined as the geographic area covered by the network of a carrier and thus it depends on the number of base stations built in an area/market. The coverage data are created from a database publicly available at the the Federal Communication Commission website. The FCC collects and publishes comprehensive data concerning the percentage of area covered by each of the 4 major carriers at the block level, distinguishing between 2G and 3G technologies.

For the purpose of this paper, I need information concerning the percentage of an area covered at the level of the Designated Market Area (DMA), the geographical area in which Nielsen collects the data reported in the Consumer Panel database. Nielsen provides DMA maps and files for mapping FIPS codes to DMA regions. The FIPS is a federal code that uniquely identifies counties in the United States.¹⁸ I use the Nielsen maps combined with the files provided by the US Census, which collect information about the blocks related to a county, and

¹⁶An active unit is a subscriber with an active SIM card.

¹⁷The ARPU is not equal to the average bill for a household or consumer as it is not equal to the bill paid by an account, which may cover several different devices, such as multiple phones (under a family plan) or multiple devices (including phones, tablets, wireless broadband modems, or other adjunct devices covered by a customer’s service plan). It assigns overall service revenue across all revenue-generating devices. It includes roaming revenues, usage fees, access and other connection fees.

¹⁸For detailed information of the FIPS classification and a list of county FIPS code see FIPS.



(a) AT&T

(b) T-Mobile

Figure 1

Note: These figures show the 3G GSM coverage for the 2 nationwide providers as of December 2018, using data from the Mobile Deployment Form 477 Databases of the Federal Communications Commission.

the information about the actual area in squared meters of each block, in order to retrieve the percentage of area covered respectively by 2G and 3G network at the DMA level. Firstly, I need to aggregate the block-level coverage data from the FCC database at the county level. For this purpose, I use the mapping tables from the Census Bureau to group the blocks in counties. I then use the FIPS codes to assign the set of counties to the corresponding Digital Market Area.

Since I don't know the distribution of base stations at the block level, I must approximate the percentage of area that is covered by each provider at the DMA level. I rely on the 15 GEOIDs¹⁹ assigned to each block to retrieve information about the actual area at the block level. Having information about the size of each block in terms of squared meters, I can determine respectively the total area and the fraction of area with coverage for each block. I then sum the area and the sub-area with coverage across blocks composing a DMA to estimate the percentage of DMA area covered by each provider. Figure 1 and figure 2 show respectively the 3G coverage of the two providers deploying the GSM standard (Figure 1) and the two providers deploying the CDMA standard(Figure 2).

The resulting data set includes detailed information on consumers and supply choices of wireless service carriers in the United States. I define a product at the carrier-market-year level, assuming that wireless service providers offer only one type of plan and consumers choose among carriers only in each market and year. My definition of a market follows the one in the Nielsen database. Nielsen collects information of consumers at the Designed Market Area (DMA) level. A DMA region is a set of counties that form a geographic area in which the local television stations hold a dominance of total hours viewed.²⁰ There are 210 DMAs covering the United States. I collect information on the households' plans purchases for 96 DMAs. I further reduce the size of the data as I select the DMAs where I have information about more than 15 individuals. Since I observe the number of handsets-carriers purchased by each household, I delete those households for which I observe

¹⁹See footnote 13 for a description of GEOID codes.

²⁰For more information on the Designed Market Area see DMA maps.

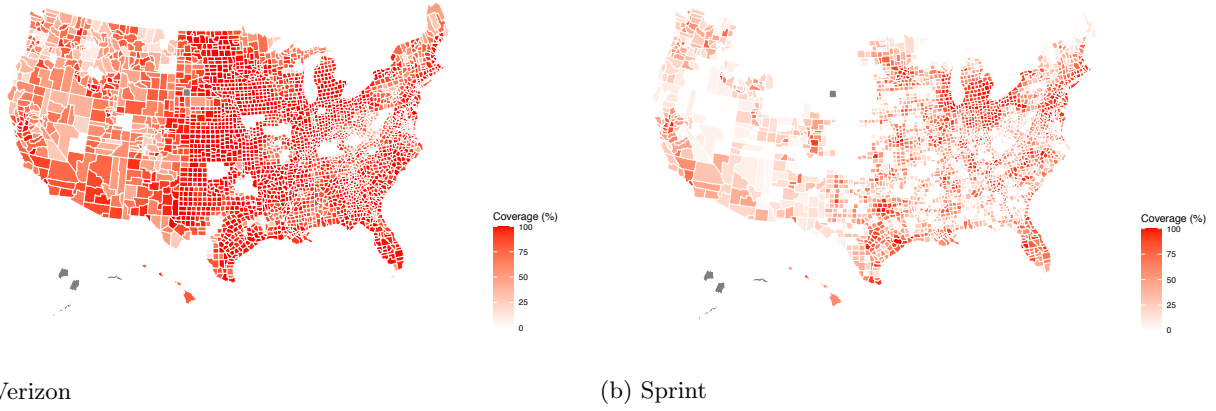


Figure 2

Note: These figures show the 3G CDMA coverage for the 2 nationwide providers as of December 2018, using data from the Mobile Deployment Form 477 Databases of the Federal Communications Commission.

a number of handset-carrier pairs greater than the household size. Since those observations are likely to be related to business subscriptions, I drop those households from my sample. This leaves a sample of 67 DMA regions²¹ for a period between 2015 to 2018. I set the size of the potential market equal to the total population in a given DMA area and a given year.

There are four major wireless carriers in the United States who own and control spectrum allocation and a wireless network: AT&T, Sprint Nextel Corp., T-Mobile USA, and Verizon Communication. They are described as nationwide since all offer wireless services in at least some portion of the western, mid-western, and eastern United States. They cover more than 97.7% of mobile subscribers in the US in the sample period.²² For this reason, I focus on the 4 major carriers and I aggregate all other carriers as being the outside option in my empirical model. Not all carriers are present in all markets; some carriers don't have any coverage in a given market, or there is no household that chooses a wireless carrier. This leads to an unbalanced dataset that in total consists of 268 market-year and 5,568 household-carrier-market-year observations in the years 2015-2018. Detailed summary statistics of the final dataset can be found in Tables 8 and 9 of the Appendix.

3 Empirical Evidence

In this section, I present empirical evidence documenting the presence of positive spillovers that arise when firms, deploying the same technology standard, share their networks. I first show that firms invested heavily to expand their network coverages in the period of interest, by making some strategic capital expenditure decisions to differentiate their service offerings from those of rivals. I then provide preliminary evidence that firms invest less in network's quality when they can free-ride on other firms' investments, through roaming agreements.

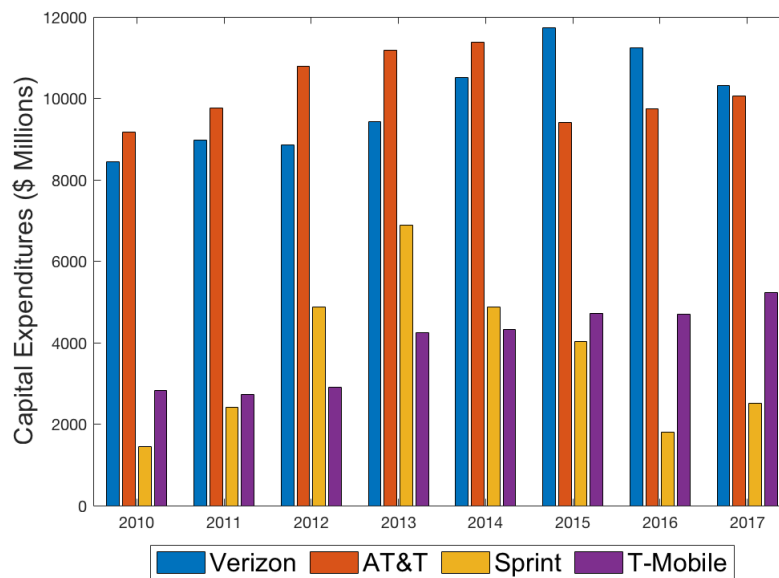
To model the investment decision of firms in coverage, firstly I need to observe an increase in the percentage

²¹The 67 DMAs correspond to the 70.08% of the whole U.S. population.

²²Datasource: FCC Eleventh to Eighteenth Reports.

of area with 3G coverage in the sample period. Starting from the late 2010s, wireless providers have expanded their network coverage and capacity through increased investment in and expansion of their existing assets and infrastructure. Over the past 8 years, mobile wireless service providers in the United States have invested, based on CTIA data²³, more than \$229.5 billion in their networks, which has resulted in higher data speeds, expanded network coverage, and increased network densification. Based on data reported in the FCC Communications Marketplace Reports²⁴, wireless service providers made capital investments of \$28.5 billion in 2017, an increase of approximately 2.3% from the \$27.9 billion invested in 2016. As shown in Figure 3, absolute capital expenditures by AT&T and Verizon consistently have exceeded those by T-Mobile and Sprint. In 2016-17, AT&T, T-Mobile, and Verizon Wireless each had investments of approximately 16.3% to 17.4% of service revenue. Investments by Sprint, on the other hand, varied considerably over the past few years, from approximately 17% of service revenue in 2015, to 7.5% in 2016, before increasing to 11% in 2017.

Figure 3
Yearly Capital Expenditures by Provider 2010-2017



Source: FCC Communications Marketplace Report and UBS data.

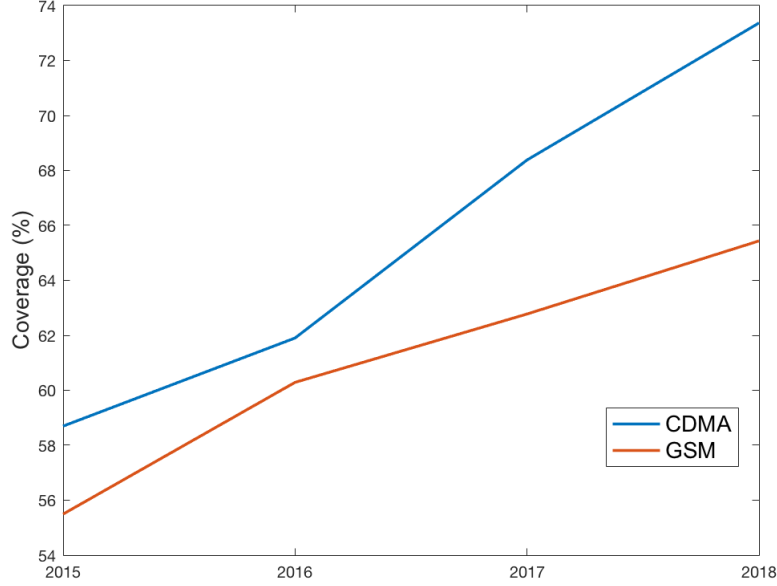
Since the capital investments in the mobile wireless service industry are consistent with the cyclical nature of technological adoption, and since firms started deploying the 4G LTE technologies in their network in 2014, the increase in investments might have driven the upgrading of their networks to the new generation technologies rather than the increase in the network coverage. Figure 4 reports the aggregate coverage available to consumers over time for each wireless 3G standard. As it shown in the figure, both the GSM and the CDMA providers

²³CTIA Wireless Industry Indices Year-End 2017. According to CTIA, the capital investment reported “excludes the cost of licenses used to deliver wireless service, whether acquired at private or public auctions, or via other acquisition processes. Likewise, investment by third-party tower erectors, and non-carrier owners or managers of networks, is not tracked by nor reflected in CTIA’s survey. CTIA’s survey collects only historical (past data) and not projected or planned investment.”

²⁴The Communications Marketplace Report replaced the Mobile Wireless Competition Report starting from 2018. The new reports of the FCC can be found at Communications Marketplace Report.

invested in their coverage in the sample period, suggesting that the a share of the capital invested was allocated to expand the provider's network coverage.

Figure 4
3G Coverage over Time, by Standard



Note: This figure shows the percentage of area with coverage available over time for each wireless standard. It reports the average across DMAs and providers deploying the same standard, using data from the Mobile Deployment Form 477 Databases of the Federal Communications Commission.

In order to find empirical evidence of free-riding between firms deploying the same standard, I estimate the following fixed-effects model at the firm-market-year level:

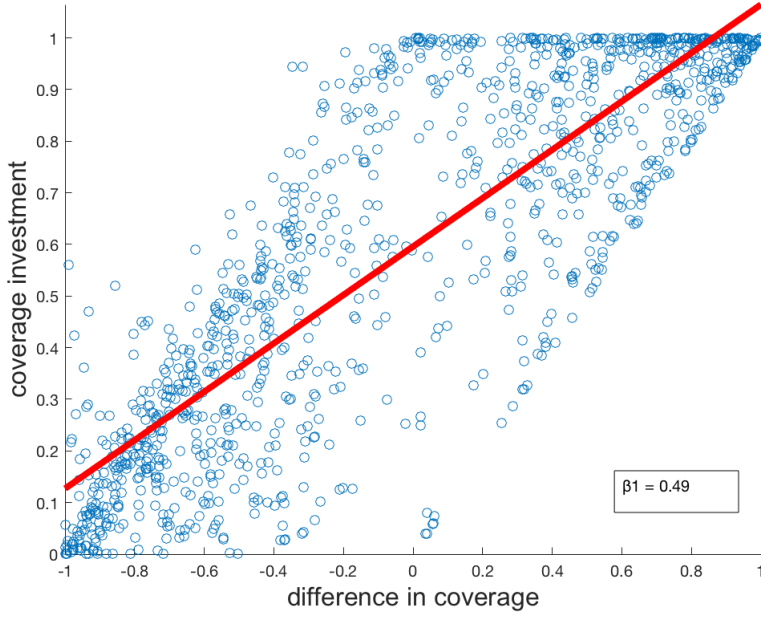
$$I_{jmt} = \beta_0 + \beta_1(x_{jm,t-1}^{3G} - x_{km,t-1}^{3G}) + \zeta_j + \eta_t + \kappa_m + \nu_{jmt} \quad (1)$$

where the dependent variable I_{jmt} is the additional coverage set by firm j in market m in year t . The covariate of interest is the difference between $x_{jm,t-1}^{3G}$, the percentage of area with 3G coverage by firm j in market m in the previous year $t - 1$, and $x_{km,t-1}^{3G}$ which measures the percentage of area with 3G coverage by firm k , deploying the same standard of j , in market m in the previous year $t - 1$. The free-riding effect between firms is represented by β_1 . A positive β_1 means that firms free-ride on the rival's investment, while a negative β_1 means that there is not any free-riding by firms. The idea behind β_1 is that, when the coverage set by a competitor is higher compared to the network infrastructure of a provider, and so the term $(x_{jm,t-1}^{3G} - x_{km,t-1}^{3G})$ is negative, the provider faces less incentives to invest in the next period since it can benefit from the rival's network. On the other hand, in the absence of a free-riding effect, firms with less coverage face higher incentives to invest in the future periods in order to reach the network quality offered by the competitor. Therefore, in this case I would expect a negative coefficient. I also control for unobserved heterogeneity in providers, markets and years, by absorbing a set of fixed-effects. I include in the regression equation a provider, ζ_j , time, η_t , and market, κ_m .

fixed effect. ν_{jmt} is the error term.

Figure 5

Empirical evidence: free-riding



Note: This figure shows the relationship between the difference in coverage between two providers deploying the same standard (x-axis), and the investment in coverage by a provider (y-axis).

Figure 5 presents estimates for Equation 1. After controlling for the heterogeneity at the provider, market and time level, I find that there is a positive relationship between the difference in the coverage set by a provider and its rival which deploys the same standard and the coverage investment of the same provider in the future period. We can see that β_1 is positive with a magnitude of about 0.5% and a strong relationship reported by a R^2 equals to 0.95. This evidence supports the hypothesis of a free-riding effect between firms within the same standard path.²⁵

4 Empirical Model

In this section, I specify a structural model of consumer choice of network providers and supply of mobile services under endogenous coverage choices, in line with the models of Goolsbee and Petrin (2004), Berry et al. (1995), Li (2017). I need a model that generates realistic substitution patterns between network providers on the demand side and that explains how firms choose the quality of their wireless network, in terms of coverage, conditional on the standard deployed. The model also needs to allow me to study the impact of a single standard policy on market outcomes and welfare.

Consumers choose the network provider which maximizes their utility and they have heterogeneous preferences over prices and quality of the service provided. Furthermore, consumers make static demand decisions each

²⁵See Table 10 in the Appendix for details on the regression output.

period. Modeling the carrier decision as static may be reasonable due to the nature of the data available. Indeed every year I have information about a different set of consumers and I, therefore, do not follow the decision of the same consumers over time. Given the static consumer demand model, I do not explicitly model the consumer switching costs among network providers. I assume that consumers only care about the coverage of the market they live in, thus markets are independent: the coverage of another market does not affect the decision of a consumer to choose a provider. Within the compatible network, consumers have access to the combined wireless network of all firms deploying the same technology standard. I thus assume consumers care about the coverage of the provider chosen as well as the coverage of the providers deploying the same standard. This assumption is based on the evidence that consumers do also have access to the network of providers deploying the same standard as the provider chosen, through roaming agreements.²⁶ Besides, the consumer model needs to predict the demand response to alternative coverage infrastructure, while accounting for the positive spillovers among firms joining the same standard path.

The supply side allows firms to compete on prices and quality, by endogenizing in the model the choices of the percentage of the geographic area with coverage in each market by the 3G technology and the choice for prices. I model firms as playing a series of static stage games; in each period, firms choose their coverage investment simultaneously, conditional on the coverage of the competitors in the given period and their own coverage in the previous period. They simultaneously set prices at the national level conditional on the coverage installed thus far. The assumption of national prices is reasonable as firms do not offer specialized plans or phones by market. The game is repeated over $T = 4$ periods. In each period $t = 1, \dots, 4$, there are 3 stages. Firms are forward-looking across stages within a time period, but not across periods. Moreover, I assume that firms have already chosen the standard technology to deploy and this decision stays constant over time. Firms stick to the choice made upon the standard. In addition, I treat the decision to invest in the 2G coverage as exogenous. In other words, I don't account for possible upgrading of the wireless networks by the carriers. I do so, first, because, given the period of interest, 2G technologies were becoming obsolete and the process of deploying 4th generation technologies had already started and, second, because when firms upgrade their network they reduce the geographical area covered by 2G technology. In this context, I would also need to model the disinvestment of firms on the supply side. Since I am interested in the investment decision of firms in coverage under a compatible network, I don't account for 2G coverage disinvestments in the supply.

The timing of the model in this industry can be summarized as follow:

1. Network providers set local network quality in each market, by adjusting the percentage of area with coverage and plan prices to maximize current-period profits
2. Consumers realize demand shocks.
3. Consumers choose a network provider to subscribe to, or an outside option, measured by other local

²⁶See the Mobile Phone Market subsection.

facilities-based providers.

4.1 Demand

A Designated Market Area m observed in year t defines a market. Each consumer i in a market chooses one option which is either the outside option $j = 0$ or one of the $j = 1, \dots, 4$ differentiated services offered by the four carriers. If the consumer chooses the outside option, it means that she decides upon one of the local providers. The utility that consumer i has by choosing the mobile carrier j in market m is given as:

$$u_{ijmt} = \underbrace{\delta_{jmt}}_{\text{mean utility}} + \underbrace{\sum_{g=2}^4 \alpha_g p_{jt} d_{gimt} + \sum_{z \in Z} \sum_{q \in Q} \sum_{r \in R} (\gamma_{qz} + \gamma_{qzr} 1_{GSM,j}) \left[x_{r(j)mt}^q z_{imt} \right]}_{\text{deviation from mean utility}} + \epsilon_{ij} \quad (2)$$

where δ_{jmt} measures the mean preferences for price and the quality of the wireless network provided by a carrier, common to all consumers in a market. The product national price and the product attributes observed in the data are denoted by p_{jt} , $x_{r(j)mt}^q$, and $1_{GSM,j}$, while z_{imt} includes the demographic characteristics of consumer i in the set Z . Specifically, I account for the age, the household size, and the income of consumers as the demographic attributes that can affect the preferences on the differentiated services in terms of coverage and technologies deployed. For instance, as the service provided is a bundle of mobile phone and data services, young people and businessmen might have strong preferences for data services over mobile voice services, while old people might prefer stable calls over a faster data rate. In addition, consumers with a higher income might prefer providers which offer both higher coverage and higher data speed, while low-income consumers must choose between the two factors. Lastly, larger families might prefer family plans compared to a family composed of two persons or singles. ϵ_{ij} is a consumer-specific unobserved taste shock consumer i has for carrier j .

Price sensitivity is allowed to vary by four consumer income levels, with the lowest income group taken as the base, and the dummy variable d_{gimt} equals one if consumer i is in the income group g and zero otherwise.²⁷ In addition, for each firm j , I interact the observed product characteristics with Z demographic variables, represented by the term $\sum_{z \in Z} \sum_{q \in Q} \sum_{r \in R} \left[x_{r(j)mt}^q z_{imt} \right]$, which allows for heterogeneous preferences by demographics. The product characteristics $x_{r(j)mt}^q$ are defined as the percentages of area covered in each market by the technology $q \in \{2G, 3G\}$ respectively, and deploying standard $r \in \{GSM, CDMA\}$. Besides, the variable $1_{GSM,j}$ equals one when provider j deploys the GSM standard in its network. The dichotomous variable allows me to capture the average preferences for providers deploying the same standard. Thus it allows me to comprise the preferences for the different technological characteristics of the two competing standards.

Following Goolsbee and Petrin (2004) and Berry et al. (1995), I decompose the mean preferences for each product in each market as a function of price, product characteristics and ξ . Consumers derive mean utility

²⁷Following the changed consumers preferences reported in the FCC reports, it can be argued that price sensitivity varies with income, but preferences towards coverage and technology vary by age and household size. Furthermore, for a theoretical foundation of the price sensitivity to income see Shaked and Sutton (1982).

δ_{jmt} as defined below:

$$\delta_{jmt} = \alpha_0 p_{jt} + \sum_{q \in Q} \gamma_q x_{r(j)mt}^q + \zeta_j + \xi_{jmt} \quad (3)$$

ξ_{jmt} represents the market area-wide average value of unobservables and omitted attributes, such as the spectrum held by each provider, the number of subscribers per provider, marketing, and advertising strategies. It is constant across consumers in the same market. Since the variable $1_{GSM,j}$ in the individual utility equation does not only capture the technological differences between standards, but it also includes other factors that are common across providers within the same technology path, I control for the carrier-specific characteristics in the mean utility function, including a carrier-specific effect ζ_j . This term allows me to control for unobservable factors of the 4 providers such as changes in phone selection, phone pricing, national advertising that are not captured in the data.

The term $x_{r(j)mt}^q$ measures the quality of the carrier's network in terms of provided coverage, and it is defined as follow:

$$x_{r(j)mt}^q = \max_{\{j:r(j)=r\}} \{x_{jmt}^q\} \quad (4)$$

where x_{jmt}^q is the quality of the 2G and 3G network respectively, for $q = \{2G, 3G\}$, of carrier j deploying standard r , defined as follow:

$$\begin{aligned} x_{jmt}^{3G} &= \sum_{c \in C_m} N_{c jmt}^{3G} \\ x_{jmt}^{2G} &= \sum_{c \in C_m} N_{c jmt}^{2G} \end{aligned} \quad (5)$$

where $N_{c jmt}$ is the percentage of block c in the set of blocks C_m in a market m covered by the carrier j .

The quality of the service provided by a carrier j depends on several factors: the coverage of the network a consumer can access, and the data speed which depends on the type of technology standard the firm deploys. I include in the utility function different variables to capture all the elements affecting the network quality. Specifically, x_{jmt}^q measures the coverage infrastructure of firm j deploying 2G technologies as well as the coverage deploying 3G technologies, and $1_{GSM,j}$ captures the average preferences for providers deploying the same technology standard, including the differences in the technological characteristics of the two standards. The parameter vector γ captures preferences for network quality, in terms of coverage and data speed. I allow consumers to vary their preferences for the 2G and 3G coverage due to the different quality that the two technologies can achieve in terms of mobile voice and data usage.

The term x_{jmt}^q measures the percentage of area with coverage, respectively deploying the 2G and 3G technologies, for a consumer choosing firm j . It distinguishes between the percentage of blocks covered by 2G and 3G technologies within a market m as well as the technology standard deployed. Due to the presence of roaming agreements between providers deploying the same technology standard, a consumer can indirectly use some of the rival's network in case her provider does not cover a particular area. In this sense, the whole network a consumer has access to comes from the combination of two components: the network of provider j and the leftover aggregate network of all providers within a market deploying the same standard as j . Since I can only observe the percentage of the geographic area covered by a provider, without observing the exact location of the base stations, I cannot infer whether the coverage of the carrier chosen overlaps or completes the network of the competitors. Moreover, given the geographical constraints exogenous to the providers and the high degrees of coverages in each market, it is likely that firms build base stations close to each other. For these reasons, I assume there is a high correlation between the geographical coverage of a provider and its competitors and therefore I measure the coverage that a consumer has by choosing firm j as the maximum value of 2G and 3G coverage, between the carrier and the competitors deploying the same technology standard.²⁸ The carrier's coverage measure becomes a standard coverage measure. Since the utility derived by j is affected by the combined investment of the firms deploying the same standard, it comprises the positive spillovers between carriers from a compatible network. For instance, when a competitor, that chooses the same standard as j increases its coverage, it will affect the quality of the network owned by j and so its utility measure for a consumer. Therefore, the γ_{qz} , γ_{qzr} and γ_q parameters reflect the free-riding effect from firms deploying the same standard: an increase of the coverage by the competitor can cause a shift outward of the demand for the carrier since it will directly increase the quality of the firm's network.

The standard Berry, Levinsohn, and Pakes models (Berry et al., 1995) assume that the unobservable taste shock is an i.i.d. type-I extreme value. Given the assumption of the independent distribution of taste shocks across providers, the correlation between choices is obtained through a function capturing the effect of the demographics and unobservable characteristics of a consumer over the taste for price and product characteristics (random coefficients model). The term allows for flexible substitution patterns. Since my specification for utility differs from the BLP equation, and it does not include any interaction between demographic characteristics and unobservables, assuming a type-I extreme value distribution of the error terms do not allow for realistic substitution patterns among carriers, which is crucial for testing a compatible policy. Nevertheless, the logit model restricts consumers to substitute towards other brands in proportion to market shares, regardless of characteristics. To estimate realistic substitution patterns, I allow the error terms to be correlated across choices following a multinomial probit model. Although computationally more demanding, a probit-type model with

²⁸Accounting for the coverage at the provider level in all markets and years, the correlation measure between the 3G coverage set by Verizon and the 3G coverage installed by Sprint, which are the two providers deploying the CDMA standard, equals 0.67. Concerning the two providers choosing the GSM standard as the technology to be deployed in their networks, the correlation between the 3G coverages is 0.33. Concerning the 2G coverages, the correlation between coverages is respectively 0.69 and 0.23.

an unrestricted (multivariate normal) covariance matrix will not suffer from the problems related to the logit model. In the case of wireless telecommunication, I believe that allowing unobserved tastes to vary product by product and to covary across products is crucial for correctly estimating flexible substitution patterns. The distribution assumption of individual unobserved attributes has important implication for the cross-elasticities: in case that the shocks to utility are not correlated across firms, the model restricts consumers to substitute towards other firms in proportion to market shares, regardless of the firm's specific characteristics.²⁹ Therefore, realistic substitution patterns are important to capture the complementarity effect in the coverage investments between firms. For this reason, the consumer-specific unobserved taste shock ϵ_{ij} is assumed to follow a multivariate normal distribution.

Lastly, I make all the normalization to the outside option; specifically I normalize the error terms ϵ of the four carriers to the ϵ_0 related to the outside option, since the variance of the error for the outside good is likely not separately identified from the others. Given the normalization, the variance-covariance matrix from the multinomial probit adds a vector of 10 parameters that are called σ .³⁰ This leads to a utility from purchasing the outside option u_{i0mt} exactly equal to zero.³¹

Consumer i in market m in year t chooses alternative $j = 0, 1, 2, 3, 4$ that maximizes her utility. Assuming that ϵ_{ij} follows a multivariate normal distribution makes the demand a multinomial probit. I can therefore derive the probability that provider j yields the highest utility across all possible alternatives, by integrating over the individual-specific valuations for characteristics:

$$Pr_{ijmt} = Pr[y_i = j] = \int_{B_{ij}} \phi(\epsilon_i) d\epsilon_i \quad (7)$$

where $B_{ij} = \{\epsilon_i | u_{ij} > u_{ik} \forall j \neq k\}$ is the set of ϵ_i such that product j provides maximum utility.

4.2 Supply

I model the profit-maximizing price and coverage decisions of firms for each year t . The model endogenizes the firm choice in the percentage of the geographic area covered by 3G technology within a market, conditional on the standard deployed by the firm and the standard deployed by competitors. The percentage of the geographic area covered allows me to capture the choice in the quantity and the location of towers of a firm, which affects

²⁹See Nevo (2000)

³⁰Following Goolsbee and Petrin (2004), and since choice data can only identify relative rankings, I assign the outside option as the reference category and I normalize the errors such that $\epsilon_i^* = (\epsilon_{at\&t} - \epsilon_0, \epsilon_{verizon} - \epsilon_0, \epsilon_{t-mobile} - \epsilon_0, \epsilon_{sprint} - \epsilon_0) \sim MVN(0, \Omega^*)$, which is distributed multivariate normal with a normalized variance covariance matrix given by:

$$\Omega^* = \begin{bmatrix} \sigma_V^2 & \sigma_{V,A} & \sigma_{V,T} & \sigma_{V,S} \\ & \sigma_A^2 & \sigma_{A,T} & \sigma_{A,S} \\ & & \sigma_T^2 & \sigma_{T,S} \\ & & & \sigma_S^2 \end{bmatrix} \quad (6)$$

³¹I make all the necessary normalization to the outside option. For instance, I set $x_{jmt} = 0$, $\beta_{0m} = 0$ and the $\xi_{0m} = 0$. This leads to the utility for purchasing the outside option $u_{i0mt} = \epsilon_{i0mt}$, but, because of the normalization of the residuals to ϵ_0 , this gives $u_{i0mt} = \epsilon_0 - \epsilon_0 = 0$.

the quality of the service provided. Nevertheless, this control variable is part of a dynamic model of quality investments that may be driven by the firm's future expectations, my static model captures all the relevant incentives faced by the firms. I assume that the investment in coverage by a firm in a period affects the firm's market share and the profit in the same period. Since I also assume that firms account for the coverage set in previous periods in their investment choice, the coverage already installed drives the increase of the market shares in future periods and so future profits. Besides, I assume a linear functional form of the per-unit investment cost. Assuming a linear cost specification of the investments with respect to coverage, it allows the firms to substitute investment costs perfectly across periods.³² Lastly, building new base stations is a costly investment decision that takes years to be realized, and so it may be driven by firms' expectations beyond the time coverage of the dataset available. Therefore the static profit function is proportional to the dynamic value function, so that optimization from the static model is consistent with a dynamic game.

In each period firms simultaneously decide the coverage-infrastructure investment I_{jmt} , taking into account the coverage already installed by the firm in the previous period and the coverage of its competitors. And, they maximize profits by setting national-level prices for the service provided p_{jt} .³³ I allow the consumers' marginal costs to vary across markets and carriers. This assumption allows me to partially account for the complex structure of plans offered by the wireless carriers when estimating the markups, which in turn affect the profit for each firm.

The profit π_{jt} of firm j in year t is given by the sum of markups over markets times the sum of the consumer's choice probability of adoption of a carrier in a market and year, minus the cost of coverage-infrastructure investment $k(I_{jmt})$:

$$\pi_{jt} = \sum_{m \in M} (p_{jt} - mc_{jmt}) s_{jmt}(p_t, x_{mt}^q, 1_{GSM}, \xi_{mt}; \theta) A_{mt} - k(I_{jmt}) \quad (8)$$

Where mc_{jmt} is a measure of the firm's specific cost per consumer, A_{mt} is a measure of the size of market m in year t , given by the total population in m and s_{jmt} is the predicted market share from the demand model for provider j in a specific market and year.

³²In fact, if investment was convex, then firms would want to invest a little bit each year to spread that cost, but this would require forward-looking firms. If investment was concave, then firms would want to do a lot of investment today, and realize that over many periods. But, since investments are linear in coverage, then I can assume that firms make static investment choices each period. Moreover, since the investment decision is continuous in coverage, investments are not lumpy, leading to small increase in coverage in each period.

³³Since prices are set at the national level, I expect that the effect of the coverage investment at the market level on the incentive to change national prices will be small. This allows me to not rely on instruments for prices in the model estimation. See the Identification subsection for a detailed explanation.

The first-order conditions (FOCs) with respect to price and coverage are then given by:

$$\begin{cases} \frac{\partial \pi_{jt}}{\partial p_{jt}} = \sum_{m \in M} A_{mt} \left[s_{jmt} + (p_{jt} - mc_{jt}) \frac{\partial s_{jmt}}{\partial p_{jt}} \right] = 0 \\ \frac{\partial \pi_{jt}}{\partial x_{j1t}^{3G}} = A_{1t} (p_{jt} - mc_{jt}) \frac{\partial s_{j1t}}{\partial x_{j1t}^{3G}} - \frac{\partial k(I_{jmt})}{\partial x_{j1t}^{3G}} = 0 \\ \vdots \\ \frac{\partial \pi_{jt}}{\partial x_{jMt}^{3G}} = A_{Mt} (p_{jt} - mc_{jt}) \frac{\partial s_{jMt}}{\partial x_{jMt}^{3G}} - \frac{\partial k(I_{jmt})}{\partial x_{jMt}^{3G}} = 0 \end{cases} \quad (9)$$

The first derivative is the usual first-order condition with respect to price for a single product firm, where firm j trades off increasing the margin on its product by increasing the price against losing market share due to this price increase, adjusted by the effect of changing j 's price on its own demand. While, when choosing the coverage in a market, the firm trades off the higher demand due to an increase in the quality of its network against the increase in the investment cost the firm faces for increasing the coverage. In this context, there is an additional effect due to compatible networks, captured by the term $\frac{\partial s_{jMt}}{\partial x_{jMt}^{3G}}$. When firms decide on the quality of the network, and so on the additional coverage to install, they account for the fact that the increase in its coverage affects the coverage available to consumers with a rival provider using the same standard. Therefore, they account for the fact that the increase in coverage can lead to consumers switching providers to them and rival providers deploying the same technology standard.

4.3 Investment cost specification

Firms choose the number of towers, and therefore the coverage, to allocate across the 67 local market networks each year. In my model, I endogenize the choice of the 3G coverage, while keeping the 2G coverage exogenous. Thus I model only the cost for increasing the percentage of the geographical area covered by the 3G technology. The investment cost k is assumed to be linear³⁴ in the percentage of area covered and depends on only the coverage chosen by the firm itself and not by the competitors' coverage. For firm j , it is given by:

$$k(I_{jmt}) = \sum_{m \in M} \lambda_1 (x_{jm,t}^{3G} - x_{jm,t-1}^{3G}) 1_{GSM,j} + \lambda_2 (x_{jm,t}^{3G} - x_{jm,t-1}^{3G}) 1_{CDMA,j} \quad (10)$$

where $1_{GSM,j}$ equals 1 if the firm chooses the GSM standard and, on the other side, $1_{CDMA,j}$ equals 1 if the firm chooses the CDMA standard. I, therefore, allow for different coverage investment costs, depending on the standard deployed. This assumption allows me to test in the counterfactuals the effect of a compatibility policy for the GSM and the CDMA standards respectively.

³⁴It is probable that consumers have decreasing marginal returns from additional coverage and firms have an increasing investment cost. These effects can be captured by allowing a more flexible functional form of the coverage in the utility equation and the cost equation. But this requires more data. Even if I could use a log form of the coverage infrastructure measure in the utility, this is not possible in the supply part, given the limited amount of data. I believe that the linear form for cost is a parsimonious structural assumption, given the available data.

Having a functional form for the investment costs allows me to express the FOCs of price and coverage by:

$$\begin{cases} p_{jt} = \mathbf{mc} - \frac{\mathbf{s}}{\frac{\partial \mathbf{s}}{\partial p}} \\ (p_{jt} - \mathbf{mc}) \frac{\partial \mathbf{s}}{\partial \mathbf{x}^{3G}} - (\lambda_1 1_{GSM,j} + \lambda_2 1_{CDMA,j}) = 0 \end{cases} . \quad (11)$$

Since standardization changes the nature of competition among firms turning investment into demand complements³⁵, the effect of a compatibility policy depends only on the demand ($\frac{\partial s_{jmt}}{\partial x_{jmt}^{3G}}$), given that the coverage of competitors does not enter the cost function.³⁶

5 Estimation and Identification

5.1 Identification

The mean utility parameters α_0, γ_q can be identified due to variation in prices, market shares, and observed network characteristics (2G coverage, 3G coverage, and standard deployed). In addition, variation in observed consumer characteristics identifies $\alpha_g, \gamma_{qz}, \gamma_{qzr}, \sigma_{A,V}, \sigma_{A,T}, \sigma_{A,S}, \sigma_{V,T}, \sigma_{V,S}, \sigma_{T,S}, \sigma_A^2, \sigma_V^2, \sigma_T^2, \sigma_S^2$. Market share variation exists across DMAs and time. So coverage, both for the 2G and 3G technologies, age, and income vary across markets and time. Moreover, coverage is constant across firms deploying the same standard. In contrast, the technology standard deployed stays constant for the sample period and does not change across markets. Prices only vary across time, but they are constant across markets.

The demand-side parameters, coupled with an assumption on firms' behavior, allow me to recover implied markups, consumers marginal costs, and investment costs. The variation in observed coverage, in the standard deployed by providers, prices, and predicted market shares allow me to identify the parameters (λ_1, λ_2) . The identification of the investment cost parameters relies on the moment conditions derived from the orthogonality assumption in Equation 10.

Following Berry et al. (1995), there might be a potential bias due first to a correlation between the national price and the unobservable product characteristics and second to a correlation between the quality of the service provided and the unobservable component of the mean preferences. Ignoring these correlations can make consumers look less sensitive on price and more sensitive on quality than what they actually are. In my specific model, the endogeneity problems are less of a concern. First, since prices are set at the national level, I expect that the effect of product characteristics at the market level, included in the carrier-market-year fixed effects δ_{jmt} , on the incentive to change national prices is small. Furthermore, it can be argued that the coverage is exogenous, due to the presence of geographical factors, that affect the quality of the carrier's network across

³⁵Under compatible technologies, firms' investments become demand complements, while under incompatibility the investments of firms deploying different standard technologies are demand substitutes.

³⁶Since I focus only on the effect of a compatibility policy on the coverage at the firm level, I define the investment cost depending only on the coverage of the carrier.

markets. Following Sinkinson (2014), firms are willing to set the maximum coverage in each market to reach high network quality, but the fact that the coverage varies across markets is evidence that there are exogenous constraints that affect the coverage set by a carrier in markets. Sinkinson (2014) identifies another source of demand shock that could be correlated with the quality of the network set by a carrier; the availability of bundled services, where consumers purchase wireless service in concomitance with other services, such as internet connection and home television, could boost the demand, affecting the incentive of a carrier to invest in coverage in specific markets. Given the data available, Sinkinson (2014) can test whether the network quality in markets where bundle services are offered differs from markets with non-bundled services. He finds no evidence of a difference in the mean quality across markets. Thus, it is unlikely that prices and coverage are correlated with the unobservable terms in my model, and therefore there is no need for a set of instruments for price and coverage to control for correlation with the structural error ξ_{jmt} in the estimation procedure.³⁷

5.2 Demand Estimation

On the demand side, the parameters to be estimated $\theta_{demand} = (\theta_1, \theta_2)$, can be categorized into the linear parameters, $\theta_1 = (\alpha_0, \gamma_q)$, and the nonlinear parameters, $\theta_2 = (\alpha_g, \gamma_{qz}, \gamma_{qzr}, \sigma_{A,V}, \sigma_{A,T}, \sigma_{A,S}, \sigma_{V,T}, \sigma_{V,S}, \sigma_{T,S}, \sigma_A^2, \sigma_V^2, \sigma_T^2, \sigma_S^2)$.

It is not straightforward to estimate the structural term ξ_{jmt} because it is not separately identified from quality in the mean preferences. The typical procedure in demand estimation, introduced in Berry et al. (1995), requires aggregate market shares, but the number of observations is not sufficient for me to confidently use the shares found therein. In this case, I have 5,568 households, which collapsed to the 1072 carrier-market-years that would have too much noise to be used in this way. I instead adapt a suggestion made as an aside in Berry (1994) and most prominently applied in Goolsbee and Petrin (2004), in which fixed effects, that are included in the individual utility, soak up all the variation at the carrier-market-year level in a first step, and then covariates of interest are regressed on these fixed effects in a second step.³⁸

In line with Goolsbee and Petrin (2004), in the first stage of estimation, for any candidate value of θ_2 and vector of mean preferences δ , I compute the probability to choose carrier j , given by

$$Pr_{ijmt} = Pr[y_i = j] = \iiint_{\hat{\mu}_{il}}^{\infty} \phi(\nu_{ik}, \nu_{il}, \nu_{im}) d\nu_{il} d\nu_{ik} d\nu_{im} \quad (12)$$

Where $\hat{\mu}_{ij} = x'_j(\beta_n - \beta_j)$ and $\nu_{in} = \epsilon_{ij} - \epsilon_{in}$ for $n = l, k, m$. Since the choice probabilities are an integral with no closed form solution, I compute it by using a frequency simulator.³⁹ I then estimate the parameters θ_2 by

³⁷For a more detailed discussion on the identification of demand and supply models with differentiated products see Berry et al. (2004) and Berry and Haile (2020).

³⁸Technically, Goolsbee and Petrin (2004) use the procedure in Berry et al. (1995), which takes the observed markets shares as given to imply unique values for the fixed effects. However, they break their estimation into two parts and do not simultaneously estimate the parameters of the endogenous variables, as in Berry et al. (1995). Closer to the estimation in Berry et al. (1995), I simultaneously estimate the individual parameters θ_2 and the fixed effects, other than the outside good, by maximum likelihood, even though it is computationally more demanding.

³⁹I use 4000 draws per consumer.

maximizing the likelihood function, which includes the product specific dummies in every market⁴⁰, over the observed individual choice probabilities. I solve the following objective function

$$\max_{\theta_2, \delta_{jmt}} \sum_{i=1}^A \ln(Pr_{ijmt}(\theta_2, \delta; x_{r(j)mt}^q z_{imt})) \quad (13)$$

This identifies all of the parameters except the ones absorbed in the fixed effects, θ_1 . Once the fixed effects δ_{jmt} are recovered, I can estimate the market level parameters θ_1 by regressing the estimated fixed effects on price and product characteristics. This second step allows me to estimate the observable mean utility parameters and the unobservable structural term ξ_{jmt} for each carrier in each market year.

5.3 Supply Estimation

Using the demand estimates, I can derive the implied markups and marginal costs. Specifically, the price coefficient and the individual probabilities allow me to construct the price elasticity, which then can be used to compute the markups and marginal costs implied by the first-order conditions of profit with respect to price, as follows:

$$mc_{jmt} = p_{jt} + \frac{1}{\int \alpha_i (1 - Pr_{ijmt})} \quad (14)$$

Since I allow for heterogeneity in the consumers, I compute the marginal costs by integrating over the different consumer types, identified by the price coefficient α_i specific for each consumer.⁴¹

I compute the coverage investment costs relying on a two-stage estimation procedure. The vector of parameters to be estimated is $\theta_{supply} = (\lambda_1, \lambda_2)$. In my model, I treat coverage as a continuous variable therefore the investment decision is continuous in coverage. To estimate the vector θ_{supply} , I rely on an algorithm based on an inner and an outer loop. The inner loop aims to compute a specific investment shock unobserved by the researcher v , for candidate values of λ_1 and λ_2 , by using an interactive algorithm to find the equilibrium coverage for each firm. The unobservable term v comprises the randomness which leads to a coverage set by the provider different from the equilibrium coverage predicted by the model. Then I can interact the computed v with the observed coverages x_{jmt}^{3G} to build moment conditions, and use them to define the GMM objective function to be minimized in the outer loop.

In the first step, I solve the first-order condition defined in Equation 11 for the unobservable vector v . Since the equation does not have an analytical solution, I employ an iterative algorithm that finds the optimal coverage for each carrier in each market. Firms play a static oligopoly game as described in Section 4. The equilibrium of the coverage-setting game depends on the market shares from the demand model and it, therefore, accounts for

⁴⁰For a very general class of choice models Berry (1994) shows that such fixed effects exist and are unique.

⁴¹Specifically the individual coefficient is defined by the sum of the baseline price coefficient α_0 and the price sensitivity depending on the consumer income group α_g .

the fact that firms can free-ride on the coverage investment of rivals deploying the same technology standard. To find an equilibrium of the firms' simultaneous-move game, I simulate firms playing iterated best-response until no firm has any profitable deviations. In each iteration, a firm conditions on the coverage investments by its competitors and itself in previous iterations to solve its coverage investment problem. For instance, at each λ and for each market m, t I use a search routine to solve for $x^{3G}(\lambda_1, \lambda_2)_{jmt}$, the optimal coverage for firm j in each market, at a candidate set of values for θ_{supply} .⁴² I then compute the v respectively for the GSM and the CDMA technologies, as the difference between observed 3G coverage and the coverage predicted by the model.

In a second step, I use the computed v and the equilibrium coverage for each carrier to calculate the moments, which I then match to key moments of the data. I rely on a minimum distance estimator to back out the structural parameters of the investment costs. Therefore, I build two moment conditions $\mathbb{E} [x^{3G}(\lambda_1, \lambda_2)_{jmt}v(\theta_{supply})] = 0$, respectively for the GSM and the CDMA standard, to obtain the GMM objective function of the form

$$\hat{\theta}_{supply} = \min_{\lambda_1, \lambda_2} v(\lambda_1, \lambda_2)' \mathbf{x}^{3G} \Phi^{-1} \mathbf{x}^{3G'} v(\lambda_1, \lambda_2) \quad (15)$$

Where Φ^{-1} is a GMM weighting matrix defined as the inverse of the variance-covariance matrix of v and x^{3G} . Through the GMM estimation, the vector of parameters θ_{supply} is chosen to make the values of predicted $N3_{jmt}$ match the observed coverage from the data. Notably, I use the two-step GMM estimator, where I use an approximation of the optimal weighting matrix based on an initial set of estimates to recover the final estimated vector of parameters.

6 Results

The estimated coefficients for the key parameters in stage 1 are reported in Table 2.⁴³ In the first stage of the demand estimation, I interact the age, household size, and income demographics with product characteristics, to capture the heterogeneity in preferences for the quality of the networks deploying different technology standards. Specifically, I include the standard deployed by a carrier, and I further distinguish between the coverage related to 2G and 3G technologies. Even though the 2G network is outdated for the period of interest, I believe it is important to include this variable as a measure of the quality of the network for each firm. Two reasons can motivate the inclusion of the 2G coverage: first firms do not fully upgrade their networks to the 3G technology, meaning that 2G network is still deployed and functioning between 2015 and 2018; second, since I don't observe the geographical area covered by a carrier within a market, but I only observe the percentage of the area covered, and given the presence of 2G network, it is likely that in some specific areas there is only 2G coverage available to consumers. In this case, a consumer would still be provided with a service but of

⁴²The idea behind is that the first-order conditions with respect to coverage, when all firms are best-responding to each other, deliver the optimal choice of x^{3G} for all firms.

⁴³As a robustness check, I estimate my model with multivariate logit. Table 12 reports the estimated parameters. As expected, the results are similar to those in Table 2.

Table 2
1st Stage parameters estimates

Explanatory Variable	Coefficient	Standard Error
Age * 2G Total Coverage	-0.0326478	0.0049
Income Group 2 * 2G Total Coverage	-0.2610839**	0.0051
Income Group 3 * 2G Total Coverage	-0.659166**	0.0060
Income Group 4 * 2G Total Coverage	-0.2645419***	0.0065
Household Size * 2G Total Coverage	0.3125377*	0.0007
Age * 2G Total Coverage * GSM	0.0459614	0.0046
Income Group 2 * 2G Total Coverage * GSM	-0.4064160***	0.0076
Income Group 3 * 2G Total Coverage * GSM	0.4307461	0.0033
Income Group 4 * 2G Total Coverage * GSM	-0.0417856*	0.0025
Household Size * 2G Total Coverage * GSM	-0.3159975*	0.0026
Age * 3G Total Coverage	0.0294350 *	0.0021
Income Group 2 * 3G Total Coverage	-0.0117567***	0.0058
Income Group 3 * 3G Total Coverage	0.0707089***	0.0238
Income Group 4 * 3G Total Coverage	-0.2203005***	0.0205
Household Size * 3G Total Coverage	-0.2279023*	0.0047
Age * 3G Total Coverage * GSM	-0.0487931	0.0044
Income Group 2 * 3G Total Coverage * GSM	0.3231561**	0.0007
Income Group 3 * 3G Total Coverage * GSM	-0.2661055	0.0004
Income Group 4 * 3G Total Coverage * GSM	0.3265179**	0.0004
Household Size * 3G Total Coverage * GSM	0.3536113**	0.0009
Price * Income Group 2	0.0584511***	0.00023
Price * Income Group 3	0.1548298***	0.00049
Price * Income Group 4	0.1538729***	0.00042
Multivariate normal		
$\sigma_{V,A}$	1.311	0.0019
$\sigma_{V,T}$	0.229	0.0009
$\sigma_{V,S}$	1.765	0.0021
$\sigma_{A,T}$	1.037	0.0017
$\sigma_{A,S}$	0.578	0.0003
$\sigma_{T,S}$	0.016	0.0023
σ_A^2	2.212	0.0051
σ_T^2	2.412	0.0012
σ_S^2	0.151	0.0015
Log likelihood	8,4288	
Observations	5,568	

Note: The method of estimation is maximum likelihood. Specification is estimated using 1072 provider-market-year fixed effects for the 67 DMA markets. A unit of observation is an available provider, market, and year. The error terms are assumed to follow multivariate normal. The variance of Verizon σ_V^2 is normalized to 1. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels. See Table 10 in the Appendix for the estimates of the fixed effects.

lower quality. Finally, I include fixed effects for each carrier-market-year pair. These control for observed and unobserved attributes that vary at the carrier-market-year level.⁴⁴

The coefficients from Table 2 do not give the marginal effects on purchase probabilities. Instead, they indicate the change in the value of the utility relative to the outside option only. Overall, the signs of the estimated coefficients are in line with my expectations. The four price coefficients imply that higher income groups are less sensitive to price than lower groups.⁴⁵ All else equal, consumers prefer the CDMA technology when accounting for the overall coverage. Decomposing the network into 3G and 2G technologies, consumers get greater utility from the GSM network deploying 3G technologies while they dislike the GSM standard when it is deployed in the 2G network, even though there is considerable heterogeneity in the population. Higher income groups get less utility from the GSM technology compared to other groups. One explanation for this could be the differences between the GSM and the CDMA standard; as highlighted in the data section, the CDMA standard allows for faster data speed, therefore it is reasonable to assume that people with higher income, who are willing to pay more for higher network quality, prefer to have better data speed. Older people are less sensitive to the technology deployed, given the coefficients for the interaction terms between age and coverage, and the interaction of the two variables with the GSM technology close to zero. However, higher age is associated with higher utility from the GSM standard. Lastly, increases in the household size are associated with increases in the utility of the CDMA relative to the GSM, even though larger families prefer the GSM technology standard when accounting for the 3G technology only.⁴⁶

All the utility measures related to the 2G technology are negative, meaning that consumers get less utility from the 2G network. The results are in line with my hypothesis. Consumers don't like to experience 2G coverage when more efficient technologies, which provide better mobile and data services, are available. However, the effect is small in magnitude, conditional on the fact that consumers have access to the 2G network only when there is a lack of coverage for 3G technology or because of congestion issues, hence in situations where they would not have had any available wireless service if the 2G network had not been in place. Besides, the estimated coefficients suggest that consumers with higher income become less sensitive to 2G coverage.⁴⁷

In contrast, all consumers get higher utility from 3G coverage. Higher income groups are more sensitive to 3G coverage compared to lower income groups. A higher individual utility related to 3G coverage is plausible since those are the consumers more demanding for a better quality of the network provided by the carrier.⁴⁸ On the

⁴⁴The fixed effects are too numerous to be reported completely. For exponential reasons, I report them in the Appendix. Instead of reporting all the 1072 estimates and standard errors, I report in Table 11 the average effect for each carrier in all markets and in parenthesis how often the estimates were estimated to be statistically significant at the 95% level.

⁴⁵Since the price sensitivity for the lowest income group is α_0 and for any other group g is $\alpha_0 + \alpha_g$, the positive and increasing parameter estimates for α_g indicate that as income increases, consumers become less price sensitive. These results are in line with the results obtained by Goolsbee and Petrin (2004) in the satellite television market.

⁴⁶Due to a large number of interactions and interplay between the first stage and the second stage in the demand model, I report the results for the 2G and 3G coverage using graphs in the Appendix. For a graphical visualization of the heterogeneous effect of network quality accordingly to the standard deployed see Figure 6, 7, and 8 in the subsection Tables and Figures in the Appendix.

⁴⁷The procedure to measure the sensitivity to 2G coverage for each income group is the same as explained for the price coefficients. See footnote 44.

⁴⁸The procedure to measure the sensitivity to 3G coverage for each income group is the same as explained for the price coefficients.

other hand, older people seem to be less sensitive to 3G coverage.⁴⁹

The parameters of the multivariate normal are reported at the bottom of Table 2. They are all significant, rejecting the restrictions typically imposed by the logit models. There is a high estimated covariance between AT&T and T-Mobile and Verizon and Sprint. One way to explain this result is that both AT&T and T-Mobile and Verizon and Sprint respectively deploy the same standard in their networks. Furthermore, since T-Mobile reports the lowest coverage across markets in the sample period while AT&T has the highest, T-Mobile is the firm that benefits the most from positive spillovers. The table also reports a large correlation between Verizon and AT&T. This finding can be explained by the fact that the two carriers, being the earlier entrants in the wireless market, have similar unobservable characteristics and market shares.

The second stage of estimation is necessary since price and coverage elasticities require estimates of α_0 and γ_q . In this second step, I regress the estimated fixed effects on the measures for network quality, price, and firm fixed effects. The estimated coefficients are consistent with my priors and they are reported in Table 3. As expected, the price enters negatively and significantly in the mean utility δ_{jmt} . Consumers like higher 3G coverage but they dislike 2G technologies.⁵⁰ Nevertheless, the mean utility associated with the 3G coverage is more than ten times higher compared to the coefficient of 2G coverage, given a higher network quality yielded by the 3G technologies. Lastly, choosing a provider which deploys the CDMA standard in its network is associated with a higher utility on average with respect to the providers using the GSM standard, given higher fixed effects for Sprint and Verizon. A possible explanation for this is related to the period of analysis and the technological characteristics of the GSM standard. In the last decades, consumers have dramatically changed the use of their phones, increasing the usage of data in contrast with mobile voice services. As reported in the FCC reports, data usage per smartphone subscriber rose to an average of 5.1 GB per subscriber per month, an increase of approximately 31% from 2016 to 2017. This was accompanied by a corresponding drop in total annual minutes of voice use of approximately 21%, and in total messaging traffic of approximately 9%. Since the CDMA technologies allow for better data speed, it is reasonable to assume that consumers on average prefer the CDMA standard.

To examine the economic magnitude of network quality, I calculate the percent change in market share given a 1% increase in the geographical area covered with 3G technology, using the observed numbers of coverage, individual probabilities of adoption of a carrier, estimated demand implied from the model, and the estimated parameters of 3G coverage. The estimated demand for a given provider is the sum of the probabilities of adoption of that provider for each individual for the appropriate year and market. I report the average demand elasticities of 3G coverage across individuals in a market-year in Table 4, in terms of percentage change in market share due to a 1% change in coverage. A 1% change of Verizon's network quality has the smallest own

See footnote 44.

⁴⁹For a graphical visualization of the effect of network quality accordingly to the standard and the technology generation deployed in the network see the subsection Tables and Figures in the Appendix.

⁵⁰The negative sign of the 2G coefficient can be explained by the fact that I observe disinvestments by firms in the 2G network in my sample period in favor of infrastructures deploying new generation technologies..

Table 3
2nd Stage estimates from fixed effects regression

	Coefficient	Standard Error
Explanatory Variable		
AT&T	0.2778	0.4005
T-Mobile	0.1469	0.4003
Sprint	0.6977*	0.3959
2G Total Coverage	-0.1048***	0.0159
3G Total Coverage	0.2973***	0.0283
Price	-0.2625***	0.0633
R2	0.781	
Observations	1072	

Note: The method of estimation is ordinary least squares. Specification is estimated using the 268 markets-years. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.

effect, leading to an increase of 0.24% in its market share. Since Verizon reports large market shares, the low elastic demand suggests the importance of its other quality dimensions unobservable to the researcher, such as spectrum and the quality of its customer services. T-Mobile has the highest effect (1.65%). The fact that T-Mobile has the more elastic demand can be explained by the lowest coverage investments by the firm in the sample period. The effect is intermediate for AT&T (1.39%) and Sprint (0.28%).

Table 4
Mean Quality Elasticities

	1 % change in network quality			
	AT&T	T-Mobile	Verizon	Sprint
Change of Market Share				
AT&T	1.3955	0.5792	-0.0891	-0.0988
T-Mobile	0.2797	1.6548	-0.0399	-0.0432
Verizon	-0.4093	-0.4132	0.2427	0.0688
Sprint	-0.2927	-0.2821	0.0491	0.2861

Note: The table shows the own (diagonal) and cross-coverage elasticities across firms. Matrices do not represent any particular market. Rather, each entry is the average individual elasticity for that particular firm.

In terms of compatibility, the demand elasticities reflect the complementarity effect related to the coverage between carriers deploying the same wireless standard. AT&T is a close complement of T-Mobile, with AT&T gaining more market share from an increase of quality by T-Mobile. In other words, raising the coverage of T-Mobile leads to a larger percentage increase in consumers shifting to AT&T, than vice versa. This factor can be explained by the fact that AT&T and Verizon have more and better spectrum than their rivals, and as early entrants may have access to better site locations compared to T-Mobile and Sprint, and thus they may offer a better service compared to their competitors. Moreover, the closest substitute of AT&T appears to be Verizon. One possible explanation is the fact that Verizon is the leader by market share in most markets in the sample, followed by AT&T.⁵¹

⁵¹This fact is confirmed by the share of subscribers at the national level as reported in the FCC reports and on the Statista website, Market Shares in the Wireless Industry.

Verizon reports a positive cross-coverage related to Sprint, since they deploy the same standard in their networks, even if it is small in magnitude. One explanation for the small value might be that the firm tends to target higher-income consumers than its less-expensive competitors, such as Sprint. Moreover, Sprint reports small cross elasticities with all other carriers. Sprint provides less mean utility to its consumers, as reported in Table 11 in the Appendix. Two factors can explain the low valuation of mean consumers; first, the small percentage of area covered in relative terms across the country, and second, the fact that Sprint is mostly present in more populated areas where there is intense competition due to the presence of regional and local providers. Given the low mean utility related to Sprint, consumers who selected that option as a carrier must have gotten a large idiosyncratic taste shock. As a result, substitution away from this firm is the lowest when rivals increase quality - these vary between -0.29% to 0.28%.

Table 5
Price Elasticities, Per-Unit Investment and Marginal Costs

Variable	Mean	Std. Err.			
Own-Price Elasticity	-0.8344	0.0041			
GSM 3G Coverage Cost	\$11,605	5.46			
CDMA 3G Coverage Cost	\$8,230	7.36			

Variable	Mean	Std. Dev.	10th Pctile	Median	90th Pctile
Price	\$440.93	185.65	68.76	544.35	667.21
Marginal Cost (average)	\$5.89	0.75	4.01	6.15	6.29
Marginal Cost Verizon	\$5.85	0.79	3.99	6.15	6.26
Marginal Cost AT&T	\$5.90	0.73	4.02	6.15	7.00
Marginal Cost T-Mobile	\$5.93	0.70	4.04	6.16	6.26
Marginal Cost Sprint	\$5.83	0.81	3.98	6.15	6.29

Note: This table reports price elasticities, per-unit coverage investment costs, prices, and consumers marginal costs calculated from the two-stages demand estimates from Table 2 and Table 3 combined with first-order conditions of the firms' profit function.

Table 5 reports the resulting estimates for the supply side. I use the demand estimates and the price first-order conditions to compute the markups and the marginal consumer costs mc_{jmt} . I allow the marginal costs for consumers to vary across markets and years. The average marginal consumer cost across providers per market-year is \$5.89. I recover per-unit coverage investment costs from the first-order conditions of the firms' profit function with respect to coverage. GSM technologies are estimated to be more costly compared to the CDMA standard. This result reflects the incompatibility of the 3G GSM technologies with the second generation networks, which made the upgrade of the 3G network more costly for the carriers following the GSM technological path. I estimate that increasing the area covered by 1% point costs about \$11,605 per year for GSM carriers while it costs \$8,230 for CDMA firms. For the validity of my investment cost estimates, since I estimate the marginal cost of increasing the coverage of 1% point and since engineering cost estimates only refer to the cost of building new base stations, I need to translate the base station cost into a cost for coverage in percentage terms. To do so, I rely on the cell sites a geographical area is divided into. I find that building a new station leads to an increase of 17% of the covered area within a market.⁵² Taking into account the total estimated costs of

⁵²For a detailed explanation of how I compute the base station-related coverage see subsection 2 in the Appendix.

building a base station by the engineering papers (Björkegren, 2019; Claussen et al., 2008; Johansson et al., 2004), an increase of 1% point of coverage costs around \$16,000.⁵³ My coverage investment cost estimates are around less than half as large as the engineering cost estimates. The difference can be driven by the limitations related to my estimation procedure of the station-related coverage. Notably, my estimation of the percentage of area covered is biased upward, given the limited available information and the fact that it does not account for decreasing marginal coverage in the number of base stations built within a market. Furthermore, the estimates for the cost of a base station are based on pecuniary costs, which are not included in my measure of coverage cost.

Table 6
Fit of the model

Variable	Model	Data
Price	\$440.93	\$418.55
3G Coverage AT&T	89.35	91.88
3G Coverage T-Mobile	22.14	20.48
3G Coverage Verizon	81.98	80.58
3G Coverage Sprint	55.05	53.35

Note: This table reports the first moments of price and coverage. It compares the aggregated moments predicted by the model with the moments calculated from the observed data.

Table 6 reports the moments in the model and in the data. Comparing the predicted and the observed prices and coverages across providers, it can be inferred that the model is able to replicate the aggregated moments in the data reasonably well.

7 Counterfactuals

In this section, I use the estimated model to quantify the effect of the counterfactual policy regime of a unified standard for wireless networks on the investment decision of carriers in coverage and welfare. In a first step, I assume that the GSM standard is the wireless standard deployed in the wireless network, and I evaluate how firms adjust their coverage investment under the GSM cost. In a second step, I assess how a compatible network under the CDMA technology affects the coverage investment of firms. Finally, I evaluate and compare the two compatibility policies with the status quo, in terms of market outcomes and welfare.

Throughout the counterfactual analysis, I assume that firms adjust their prices and coverage but the per-unit investment costs for coverage infrastructure are held fixed. Under a single compatible network, firms lose one dimension of product differentiation, related to the different technological characteristics of the two standards deployed in the status quo. Therefore, coverage, price, and the unobservable quality dimensions, such as spectrum and customer care, increase in importance for the consumer utility.

⁵³Claussen et al. (2008) estimate a cost of \$ 285K for 15 years, while Johansson et al. (2004) find a cost of \$ 266K for macro base stations.

7.1 Procedure

Having estimates of price and 3G coverage semi-elasticities, a system of first-order conditions for price and 3G coverage, and estimates of marginal consumer costs and per-unit coverage investment costs for each standard deployed in the wireless network, I can compute the new equilibrium vectors of price and 3G coverage. I employ an interactive algorithm, similar to what I use for the first stage in the estimation of the supply side, to find the new equilibrium vector of prices and coverages $(\mathbf{p}, \mathbf{N3})$. At each iteration h , I proceed as follows:

1. Use the FOCs to compute p^{h+1} , given marginal costs and market share determined in iteration h . Therefore $p^{h+1} = mc + \rho^{-1}s(p^h, N3^h)$, where ρ defines the ownership structure.
2. Update market shares and elasticities with p^{h+1} and $N3^h$
3. Use the FOC to compute $N3^{h+1}$, under the new equilibrium price p^{h+1} . As for the estimation of investment costs, I allow firms to play a simultaneous-move game to find the optimal coverage $N3^{h+1}$ for each carrier.
4. Update market shares with p^{h+1} and $N3^{h+1}$
5. Let $d_{max} = \max(d_p^h, d_{N3}^h)$, where $d_p^h = \max |p^{h+1} - p^h|$ and $d_{N3}^h = \max |N3^{h+1} - N3^h|$
6. Look for convergence between h and $h + 1$ iterations according to a criterion $\epsilon^{convergence}$. Thus, if $d_{max} \geq \epsilon^{convergence}$, go back to the initial step 1 and begin a new iteration. If $d_{max} < \epsilon^{convergence}$, extract $(\mathbf{p}^{h+1}, \mathbf{N3}^{h+1})$ to be the new equilibrium price and coverage.

Since I allow firms to adjust both price and 3G coverage, the algorithm I use relies on an inner loop where I iterate until convergence on price, before iterating until convergence on coverage, and repeat both iterations until the outer loop converges. The fact that firms choose only the coverage of the 3G network reduces the number of additional FOCs to iterate in addition to the price FOCs. I initialize the optimization routine from the price and the coverage observed at time $t = 2015$, therefore I rely on the values in the data in the first year of the sample period as starting values. I perform the counterfactuals for all 67 DMA markets in the sample period of 4 years. I adapt the algorithm for counterfactuals to rely on different initial values for price and coverage. I find that this procedure converges to the same vector of prices and coverages levels even when I start from different starting values in different counterfactual settings deploying respectively the GSM and the CDMA standard, which I take as a sign that there exists a unique counterfactual equilibrium.⁵⁴

For the counterfactual exercise, I assume that under compatibility, the four network providers set up a roaming agreement with transfer prices set to zero that allows providers to share all the four networks and consumers to access the combined investment of all four providers. I remain agnostic on how to achieve compatibility. One

⁵⁴I further adapt the algorithm in which only coverage is allowed to be re-adjusted simply by using the respective FOCs only. The results are reported in Table 13 in the Appendix.

policy option is to mandate a technology standard by policymakers, which imposes to the firms the technology standard to deploy in their network. This option is in line with the stronger policy adopted by the European Union, which imposed the GSM standard as the technology to be deployed in the wireless networks. Besides, there are two natural ways to coordinate on a single standard. The first is decentralized choices, where compatibility is the optimal outcome of the coordination game between firms. The second coordination mechanism to a single standard is based on consensus in a Standard Setting Organization.⁵⁵ The precise nature of the selection process, as well as the related costs and benefits, is outside the purpose of this project.⁵⁶ My estimated welfare impacts serve as a threshold value in comparing a market characterized by a single standard and markets with underline multiple standards, in the confines of my model and its assumptions.

Since my estimation procedure relies on the probit model, to compute the change in consumer surplus in any counterfactual scenario from the status quo I cannot rely on the standard formula for the logit model, as shown by Small and Rosen (1981) and Williams (1977). Instead, I need to numerically compute the utilities for each individual in the two scenarios. Following the same process as for the first stage of the demand side, for 4000 draws, I compute the maximum utility related to carrier j for each draw. I then take the average of the maximum utilities. Social welfare is the sum of consumer welfare and producer profits.

7.2 Compatible networks with fixed investment costs

This subsection presents the results from simulating outcomes for two single standard regimes, holding the per-unit investment costs for coverage fixed at the status quo. I compute the new equilibrium prices, coverages, and profits as well as the differences in consumer and total surplus, allowing firms to adjust their prices and coverage under the GSM and the CDMA compatible network.

Table 7 presents and compares the counterfactual outcomes from each of the three regimes with fixed per-unit investment costs: (1) Two competing wireless standards, (2) a Single GSM standard network, and (3) a Single CDMA standard network. Under a compatibility policy, both a GSM network and a CDMA network achieve higher total surplus and higher overall producer surplus. I find that a single technology standard improves total welfare by \$2.2 billion under a GSM standard and by \$8.4 billion under the CDMA standard. However, not all firms are better off under compatibility. T-Mobile loses profits deploying the GSM standard because it loses one dimension of product differentiation. Besides, a GSM network results in about \$1.77 billion lower consumer surplus than under networks using multiple standards. On the contrary, a network deploying only the CDMA technology standard achieves \$2.19 billion higher consumer surplus than incompatible networks.

Compatibility changes the nature of competition among firms, turning investments in coverage infrastructure

⁵⁵See Leiponen (2008) for details on the negotiation in Standard Setting Organizations of standards in the wireless telecommunications industry.

⁵⁶See Farrell and Simcoe (2012) for a discussion on the paths to compatibility.

from demand substitutes to demand complements. When a firm increases the coverage under compatibility, it improves the product quality of its competitors. Therefore, firms have a less business-stealing motive to invest in coverage infrastructure. In line with what the theory predicts, firms invest 20.01% less on average in coverage with the GSM standard and 9.78% less under CDMA. The high difference between the two compatibility regimes can be explained by the higher per-unit investment cost firms pay for the GSM coverage, as estimated by the structural model, that can lower the firms' incentives to invest in coverage infrastructure, aside from the lower incentive faced by the firms under compatibility.⁵⁷

The annual average price increases for the two providers deploying the GSM standard in the status quo and it decreases for Verizon and Sprint in the GSM network. It decreases for all four nationwide network providers under the CDMA technology standard. One explanation for the increase in the price of AT&T and T-Mobile with a compatible GSM network could be the starting values of the optimization problem. To evaluate the counterfactual outcomes, I account for the coverage set by the providers to 2015; the investment decision by firms until 2015 has been affected by the presence of two standards, and thus by two different investment costs. The two GSM providers might have invested too much compared to the optimum values under multiple standards such that, when they move to a single standard, they need to account for the higher investment costs paid in the years before 2015 in contrast to the 2 CDMA providers. Therefore, in the case of a single standard scenario, the equilibrium prices for those firms increase as they need to recover the investment made in a multiple-standard market while losing one dimension of horizontal differentiation. On the other hand, firms, that deployed the CDMA standard before 2015, benefit from the large investments of the two GSM competitors through network sharing. Since those firms paid lower investment costs for their coverage set before 2015, they can ask for lower equilibrium prices under a single standard policy.⁵⁸

The analysis highlights two mechanisms in the market for wireless services, which depend on the technology to deploy in the network. Under the GSM regime, firms face higher investment costs, and therefore they have incentives to invest less in the GSM network compared to the CDMA scenario. The decrease in the firm's coverage investment under the GSM standard is twice as much as the decrease in the investment under the CDMA standard. Even though the resulting network for consumers is higher in quality under a unified standard, the substantial lowering in the coverage infrastructure investment and the consequent decrease in the quality of the service provided by each provider is not compensated by a drop in the average prices, which in turn decreases the surplus for consumers. Furthermore, under a single standard policy consumers lose one dimension of the product differentiation. Consumers lose utility when they lose a variant of the product supplied in the market. Accounting for the technological differences between the two standards and the different tastes of consumers, consumers who prefer the CDMA standard in the status quo might lose more utility when they are locked into

⁵⁷The lower incentive faced by the firms due to a higher investment cost for the GSM technologies compared to the CDMA technologies can bias the estimates in coverage upwards. This highlights the need to test for a scenario where it allows for lower investment costs under compatibility.

⁵⁸The studied market is complex, and there might be other factors driving the increase in the equilibrium prices. Further research is needed to better understand the underline mechanisms.

Table 7
Counterfactual Market Outcomes

	Simulated Counterfactual Outcomes			Difference Across Regimes	
	Multiple Standards (I)	Single Standard (GSM)	Single Standard (CDMA)	(GSM-I)	(CDMA-I)
A. SOCIAL WELFARE (\$millions)					
Δ Social Welfare	-	-	-	+2227.1	+8433.4
Δ Consumer Surplus	-	-	-	-1765.7	+2186.4
Δ Producer Surplus	-	-	-	+4149.8	+6246.9
Profits					
AT&T	3040.49	3180.66	3267.31	+4.61%	+7.46%
T-Mobile	1349.42	1200.98	1411.09	-11.00%	+4.57%
Verizon	3355.78	3572.56	3647.40	+6.46%	+8.69%
Sprint	1284.56	1358.04	1451.04	+5.72%	+12.96%
B. COVERAGE INVESTMENT (%)					
AT&T	98.86	64.35	88.04	-34.91%	-10.94%
T-Mobile	62.53	42.50	50.92	-32.03%	-18.56 %
Verizon	91.58	88.50	89.77	-3.36%	-1.98%
Sprint	75.60	68.24	69.81	-9.73 %	-7.66 %
C. ANNUAL PRICE (\$)					
AT&T	409.56	410.87	400.30	+0.32%	-2.26%
T-Mobile	413.78	418.87	409.97	+1.23%	-0.92%
Verizon	453.41	450.28	432.92	-0.69%	-4.52%
Sprint	389.88	374.52	356.58	-3.94%	-8.54%

Notes: This table presents counterfactual market outcomes with (1) Two competing wireless standards, (2) GSM standard network, and (3) CDMA standard network. Columns (4) and (5) compare outcomes across regimes. The values reported in the table refer to the means across markets.

the GSM standard compared to the loss in the utility measure of consumers who choose the GSM standard when the CDMA technology is the standard deployed in the compatible network. Under GSM compatibility consumers are worst off, even if the resulting total surplus is higher.

8 Conclusion

In this paper, I study the firms' investment decisions in a market where there are underline incompatible technologies, and how the firms' investment incentives change when previously incompatible goods become compatible. I provide new insights into the debate around the welfare implication of a compatibility policy by studying how firms adjust the price and coverage in response to a single standard in the wireless industry. The wireless telecommunications market is an important market to understand because mobile wireless services have become an important part of daily lives, and competition in the provision of mobile wireless services drives innovation and investment to the ultimate benefit of consumers and society.

I develop a structural model of demand and supply for mobile wireless services and estimate it using a novel data set at the consumer level in the U.S. On the demand side, consumers choose between providers deploying different technology standards in their network. The demand side allows for rich substitution patterns across providers and technology standards. On the supply side, firms compete in national-level prices and set local network quality in each market, by adjusting the percentage of area with coverage. The model provides a framework for analyzing the impact of compatibility under different standards in imperfectly competitive markets when firms choose the price and product attributes.

I find that a compatibility policy is the welfare superior policy, regardless of the standard chosen. Whereas the overall producer surplus is higher when moving to uniform wireless networks, not all firms are better off under a compatible network. The lower profits for T-Mobile, in the counterfactual analysis, might explain why a decentralized choice did not yield a coordinated outcome in the U.S. telecommunications market, even under strong network effects. These results also advocate a necessary intervention by the government to mandate compatibility. Besides, the counterfactual analysis underlines a heterogeneous effect of a single standard policy regime on consumers: whether consumers benefit from compatibility depends on the technology chosen. These results raise questions for policymakers regarding a mandated standard policy. Therefore, mandating standards might lock in an industry in a standard (Farrell and Saloner, 1985) which leads to lower consumer welfare.

Bibliography

- BERRY, S., J. LEVINSOHN, AND A. PAKES (1995): “Automobile prices in market equilibrium,” *Econometrica: Journal of the Econometric Society*, 841–890.
- (2004): “Differentiated products demand systems from a combination of micro and macro data: The new car market,” *Journal of political Economy*, 112, 68–105.
- BERRY, S. T. (1994): “Estimating discrete-choice models of product differentiation,” *The RAND Journal of Economics*, 242–262.
- BERRY, S. T. AND P. A. HAILE (2020): “Nonparametric identification of differentiated products demand using micro data,” Tech. rep., National Bureau of Economic Research.
- BJÖRKEGREN, D. (2019): “The adoption of network goods: Evidence from the spread of mobile phones in Rwanda,” *The Review of Economic Studies*, 86, 1033–1060.
- CABRAL, L. AND D. SALANT (2014): “Evolving technologies and standards regulation,” *international Journal of industrial organization*, 36, 48–56.
- CLAUSSEN, H., L. T. HO, AND L. G. SAMUEL (2008): “An overview of the femtocell concept,” *Bell Labs Technical Journal*, 13, 221–245.
- CRAWFORD, G. S., O. SHCHERBAKOV, AND M. SHUM (2019): “Quality overprovision in cable television markets,” *American Economic Review*, 109, 956–95.
- FAN, Y. (2013): “Ownership consolidation and product characteristics: A study of the US daily newspaper market,” *American Economic Review*, 103, 1598–1628.
- FARRELL, J. AND G. SALONER (1985): “Standardization, compatibility, and innovation,” *the RAND Journal of Economics*, 70–83.
- FARRELL, J. AND T. SIMCOE (2012): “Four paths to compatibility,” in *The Oxford Handbook of the Digital Economy*, Oxford University Press Oxford, UK, and New York, 34–58.
- GANDAL, N., D. SALANT, AND L. WAVERMAN (2003): “Standards in wireless telephone networks,” *Telecommunications Policy*, 27, 325–332.
- GOOLSBEE, A. AND A. PETRIN (2004): “The consumer gains from direct broadcast satellites and the competition with cable TV,” *Econometrica*, 72, 351–381.
- HO, K. (2006): “The welfare effects of restricted hospital choice in the US medical care market,” *Journal of Applied Econometrics*, 21, 1039–1079.
- ISHII, J. (2005): “Compatibility, competition, and investment in network industries: ATM networks in the banking industry,” *Unpublished working paper*.

- JOHANSSON, K., A. FURUSKAR, P. KARLSSON, AND J. ZANDER (2004): “Relation between base station characteristics and cost structure in cellular systems,” in *2004 IEEE 15th International Symposium on Personal, Indoor and Mobile Radio Communications (IEEE Cat. No. 04TH8754)*, IEEE, vol. 4, 2627–2631.
- KATZ, M. L. AND C. SHAPIRO (1985): “Network externalities, competition, and compatibility,” *The American economic review*, 75, 424–440.
- KNITTEL, C. R. AND V. STANGO (2008): “Incompatibility, product attributes and consumer welfare: evidence from ATMs,” *The BE Journal of Economic Analysis & Policy*, 8.
- (2011): “Strategic incompatibility in ATM markets,” *Journal of Banking & Finance*, 35, 2627–2636.
- LEE, R. S. (2013): “Vertical integration and exclusivity in platform and two-sided markets,” *American Economic Review*, 103, 2960–3000.
- LEIPONEN, A. E. (2008): “Competing through cooperation: The organization of standard setting in wireless telecommunications,” *management science*, 54, 1904–1919.
- LEONARD, N. (2009): “Setting the Standard: Two Generations of Wireless Telecom,” .
- LI, J. (2017): “Compatibility and investment in the us electric vehicle market,” *Job Market Paper*, 23.
- MACHER, J., J. W. MAYO, O. UKHANEVA, AND G. WOROCH (2019): “Demand in a portfolio-choice environment: The evolution of telecommunications,” *Georgetown McDonough School of Business Research Paper*.
- NEVO, A. (2000): “A practitioner’s guide to estimation of random-coefficients logit models of demand,” *Journal of economics & management strategy*, 9, 513–548.
- SHAKED, A. AND J. SUTTON (1982): “Relaxing price competition through product differentiation,” *The review of economic studies*, 3–13.
- SINKINSON, M. (2014): “Pricing and entry incentives with exclusive contracts: Evidence from smartphones,” *Available at SSRN 2391745*.
- SMALL, K. A. AND H. S. ROSEN (1981): “Applied welfare economics with discrete choice models,” *Econometrica: Journal of the Econometric Society*, 105–130.
- WILLIAMS, H. C. (1977): “On the formation of travel demand models and economic evaluation measures of user benefit,” *Environment and planning A*, 9, 285–344.
- ZHU, T., H. LIU, AND P. K. CHINTAGUNTA (2011): “Wireless Carriers’ Exclusive Handset Arrangements: An Empirical Look at the iPhone,” *Available at SSRN 1962799*.

9 Appendix

9.1 A simple model of quality for firm

In this subsection, I outline a simple example. This simple version of the model helps to understand the forces at work under a compatibility policy.

Let there be two providers $j = 1, 2$, two standards available, and just one market. I also drop the time index for simplicity. Each firm chooses the price p and the quality N for a single product offered to final consumers in one market. The firm j 's profit maximization problem is given by:

$$\max_{p_j, N_j} \pi_j = (p_j - mc_j) s_j(p, N, \xi; \theta_2) - c(i_j) \quad (16)$$

where p_j and N_j denote the own-firm price and coverage (quality) respectively, and p and N the price and coverage vectors of the two firms in the market. s_j measures the market share of firm j , which is a function of own and competitor's prices and coverage, and $c(i_j)$ is the function of the cost of firm j to provide coverage N (coverage investment cost). Note that in this example the cost is a number and not a vector since I am assuming there is only one market. I further assume that prices and marginal costs occur at the national level and that the market population is normalized to 1.

The FOCs for firm 1 are then given by:

$$\begin{aligned} \pi_{1p_1} &= s_1(p, N, \xi; \theta_2) + (p_1 - mc_1) \frac{\partial s_1}{\partial p_1} = 0 \\ \pi_{1N_1} &= (p_1 - mc_1) \frac{\partial s_1}{\partial N_1} - \frac{\partial c(i_1)}{\partial N_1} = 0 \end{aligned} \quad (17)$$

What happens when the policymaker mandates one single standard in the market? What is the effect of a mandated standard on the profits of firms? And on the incentive to invest in coverage? As stated above, the investments of firms become complements under compatibility and since the coverage of rival enters only the market share of firm 1, the effect of a mandated standard depends only on how the variation in N_2 will affect the demand function of firm 1.

To calculate the sensitivity of firm 1's price and coverage to changes in the coverage of firm 2, I have to compute the second-partial derivatives of the profit function. The second-order derivatives of the profit function will depend on the effect of own price and quality on own demand, but also on rival product price and quality through the demand function, as the rival quality does not enter the coverage cost function.

In case the two providers decide to deploy 2 different standards, i.e incompatibility policy, then the investments

in coverage by the two firms are demand substitute and consumers don't care about the coverage of the rival when evaluating the quality of the service provided by a firm. Therefore, the g function, which measures the complementarity coverage, equals 0 for firm 1 and the coverage of the competitor enters only the denominator of the market share of firm 1 (the standard BLP model). On the other hand, under compatibility, i.e. the two firms decide to deploy the same standard, then the investment in coverage by firm 2 improves the quality and so the coverage of firm 1. In this case, the g function is different from 0 and so the coverage of firm 2 enters both the numerator and denominator of the market share of firm 1.

Differentiating the system of first-order conditions gives:

$$\begin{bmatrix} \frac{\partial p_1}{\partial N_2} \\ \frac{\partial N_1}{\partial N_2} \end{bmatrix} = \begin{bmatrix} \frac{\partial^2 \pi_1}{\partial p_1 \partial p_1} & \frac{\partial^2 \pi_1}{\partial p_1 \partial N_1} \\ \frac{\partial^2 \pi_1}{\partial p_1 \partial N_1} & \frac{\partial^2 \pi_1}{\partial N_1 \partial N_1} \end{bmatrix} \begin{bmatrix} -\frac{\partial^2 \pi_1}{\partial p_1 \partial N_2} \\ -\frac{\partial^2 \pi_1}{\partial N_1 \partial N_2} \end{bmatrix} \quad (18)$$

Where

$$\begin{aligned} \pi_{pp} &= 2 \frac{\partial s_1}{\partial p_1} + (p_1 - mc_1) \frac{\partial^2 s_1}{\partial p_1 \partial p_1} \\ \pi_{pN_1} &= \frac{\partial s_1}{\partial N_1} + (p_1 - mc_1) \frac{\partial^2 s_1}{\partial p_1 \partial N_1} \\ \pi_{N_1 N_1} &= (p_1 - mc_1) \frac{\partial^2 s_1}{\partial N_1 \partial N_1} - \frac{\partial^2 c_1}{\partial N_1 \partial N_1} \\ \pi_{N_1 N_2} &= (p_1 - mc_1) \frac{\partial^2 s_1}{\partial N_1 \partial N_2} \\ \pi_{pN_2} &= \frac{\partial s_1}{\partial N_2} + (p_1 - mc_1) \frac{\partial^2 s_1}{\partial p_1 \partial N_2} \end{aligned} \quad (19)$$

This gives

$$\begin{aligned} \frac{\partial p_1}{\partial N_2} &= \frac{1}{\pi_{pp} \pi_{N_1 N_1} - \pi_{pN_1}^2} (\pi_{pN_1} \pi_{N_2 N_1} - \pi_{N_1 N_1} \pi_{pN_2}) \\ \frac{\partial N_1}{\partial N_2} &= \frac{1}{\pi_{pp} \pi_{N_1 N_1} - \pi_{pN_1}^2} (\pi_{pN_1} \pi_{N_2 N_1} - \pi_{pp} \pi_{N_1 N_2}) \end{aligned} \quad (20)$$

Note that the second-order conditions require $\pi_{pp} < 0$ and $\pi_{N_1 N_1} < 0$ to assure a maximum for price and coverage. So the sensitivity of changes in the coverage of firm 1 due to changes on the coverage of 2 (the sign of $\frac{\partial N_1}{\partial N_2}$) depends on whether p and N_1 are strategic complements or substitute and, most important, whether we are in a compatible or incompatible market: if there is compatibility then N_1 and N_2 are complements and $\pi_{N_1 N_2} > 0$ and the other way around for substitutes. Furthermore, the sign of the cross partial derivative of profit with respect to coverage depends entirely on the cross partial derivate of the demand function $\frac{\partial^2 s_1}{\partial N_1 \partial N_2}$ which is positive in case of compatible networks. Lastly in the main model, the compatible effect is identified by the parameters measuring the sensitivity of the f function and specifically the heterogeneous parameters σ_f .

9.2 Base stations coverage measure

Mobile telephony is called “cellular” in the United States due to the practice of dividing space up into discrete “cells” served by separate base stations. Each grouping or “cluster” of base stations has access to all the firms licensed frequency. If consumers move out of the range of a cluster’s cell into a new area, they are simply transferred to the cell that covers that area and its assigned frequency. In this way, a firm can reuse a limited amount of frequency, and this innovation made mass adoption of mobile phones possible.

To measure the geographical area covered by a new base station, I assume a completely flat terrain. Therefore the most efficient base station deployment distribution has base stations at the centers of identical regular hexagons that tile the space completely. For this reason I further assume that a new base station is built at the center of each hexagon and that each base station increases the area covered equally, ie there are not decreasing marginal coverage from additional stations.

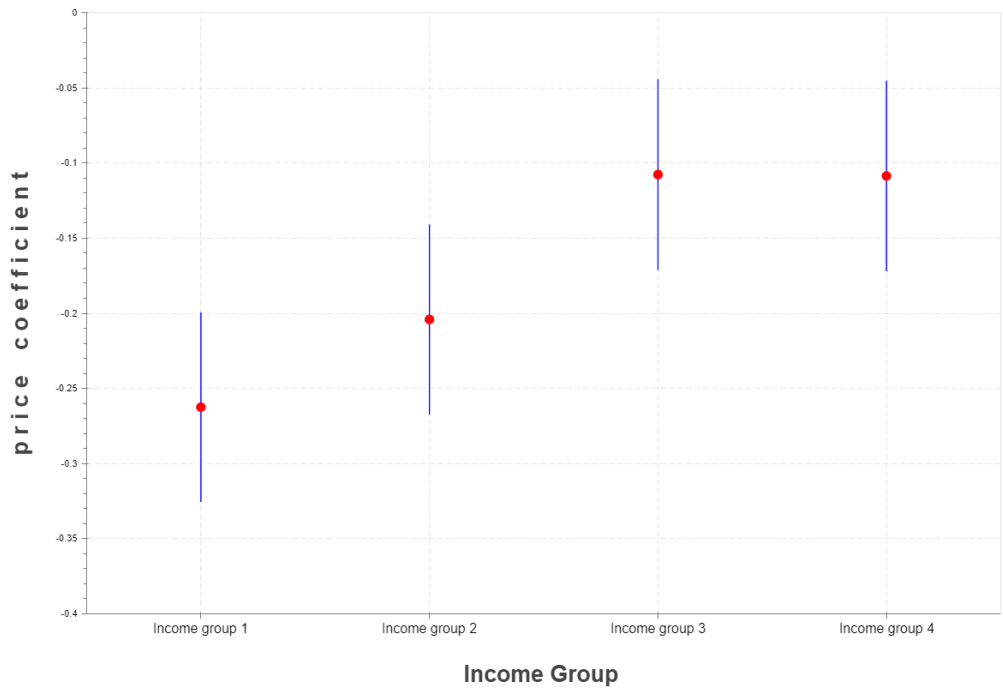
Since hexagons are regular geometrical figures, to determine the area covered by a base stations I can divide each hexagon into 12 similar right triangles with base of length a , height of length $b = \sqrt{3}a$ and side $c = 2a$. According to engineers and industry experts, the maximum distance the signal can be transmitted from a base station ranges between 35.5 and 72.5 kms. The maximum distance depends on several factors such as the geographical conformation of the territory and the technology deployed in the wireless network. Given my assumptions, I take into account an average distance of 54 kms. This leads to $a = 27$, $b = 46.77$ $c = 54$ kms, and an area of the right triangle equals to:

$$Area_{abc} = \frac{a * b}{2} = \frac{27 * 46.77}{2} = 631.39km^2 \quad (21)$$

Given the area of each triangle, I can compute the area of the hexagon given by $Area_{abc} * 12$. I then transform the coverage in terms of percentage points taking into account the area of each DMA and then taking the mean. I obtain that a new base station leads to a constant increase in coverage of 17.5% across markets on average.

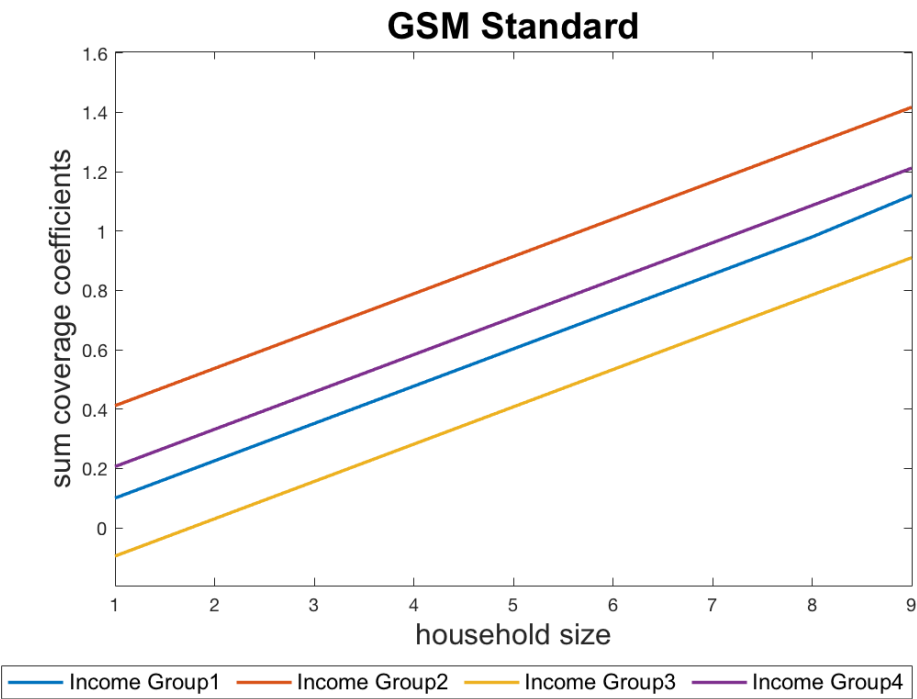
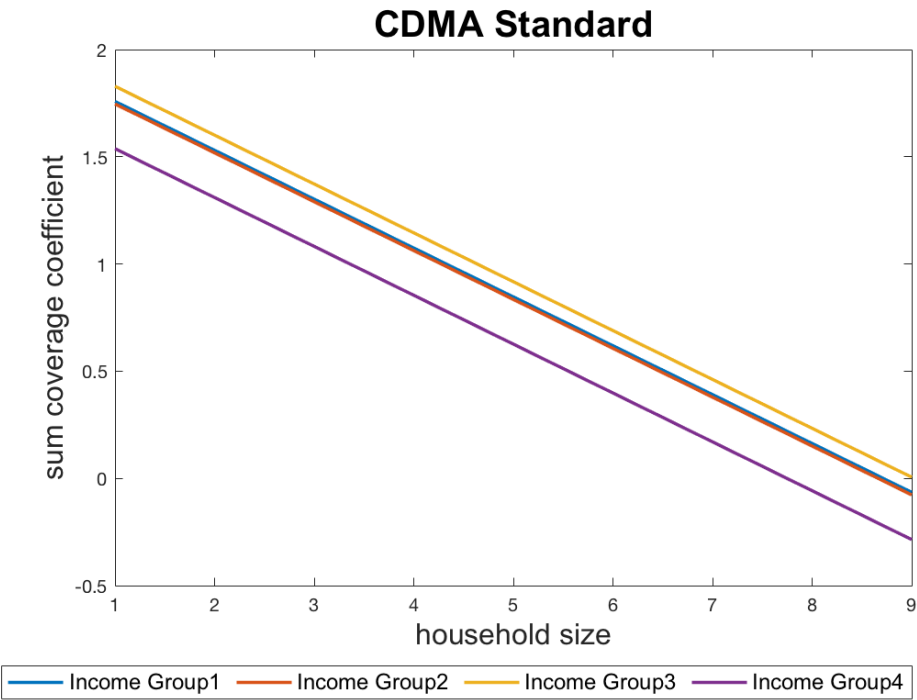
9.3 Tables and Figures

Figure 6
Demand model results: price effect by income group



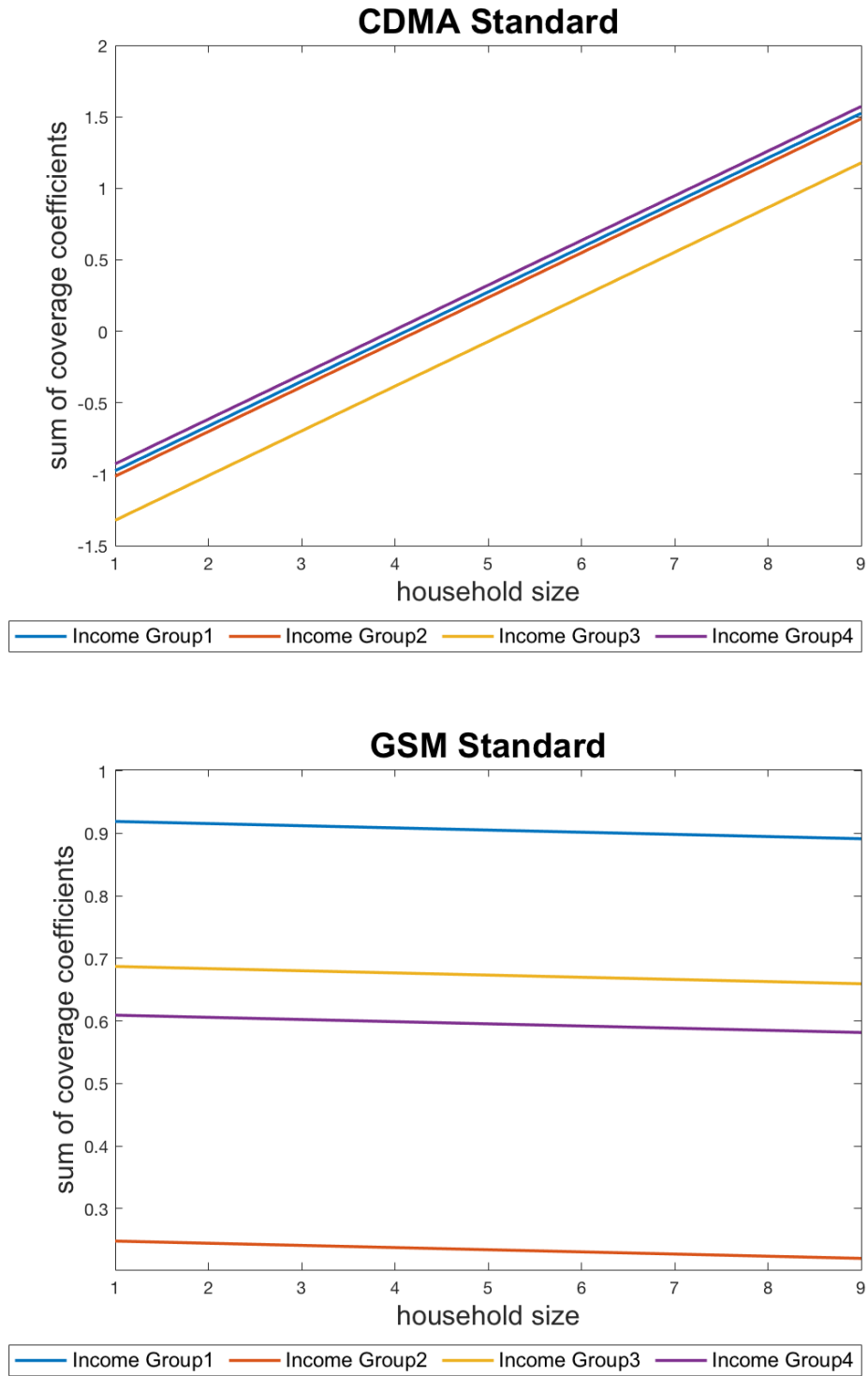
Note: This figure plots the price coefficients across income groups, aggregating the price coefficients estimated in the first and in the second stage of the demand model. The vertical lines report the standard errors.

Figure 7
Demand model results: CDMA 3G coverage effect by income group

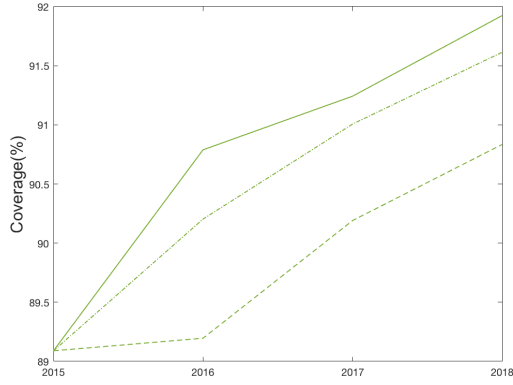


Note: These figures plot the 3G coverage coefficients from the first and the second stages of the demand model across income groups. They compare the preferences for CDMA and GSM standard. Age is held fixed, while household size is allowed to vary across individuals.

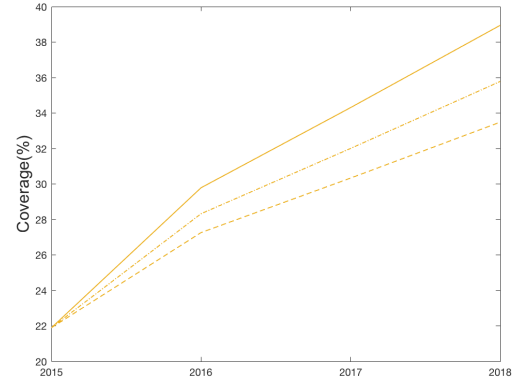
Figure 8
Demand model results: 2G coverage effect by income group



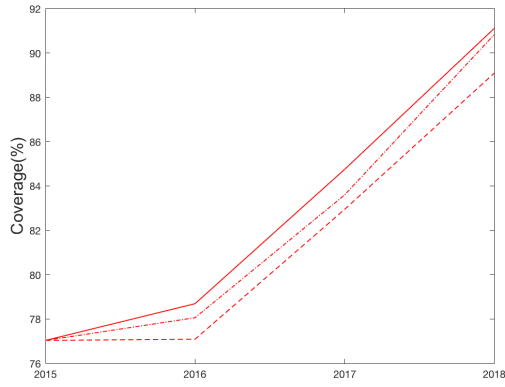
Note: These figures plot the 2G coverage coefficients from the first and the second stages of the demand model, across income groups. They compare the preferences for CDMA and GSM standards. Age is held fixed, while the household size is allowed to vary across individuals.



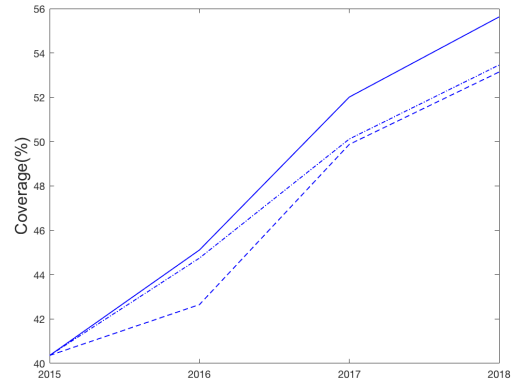
(a) AT&T



(b) T-Mobile



(c) Verizon



(d) Sprint

Note: This figure shows the counterfactual coverage for each of the four providers, holding investment costs fixed. The solid lines represent coverage in the status quo with 2 incompatible standards, the dashed lines are the counterfactual coverage for GSM, and the dash-dotted lines are the counterfactual coverage for CDMA.

Table 8
Summary Statistics - Key Variables 2015-2018

	2015	2016	2017	2018
Number of Markets (total)	67	67	67	67
Number of Urban Markets (total)	35	35	35	35
Number of Carriers per Market	4.55	4.36	4.33	4.64
Number of Markets per Carrier (total)	61.0	58.4	58.0	62.2
Number of Consumers (total)	1965	1233	1188	1182
Price	449.52	419.79	411.48	393.39
2G Coverage per Market (average across carriers)	68.37	65.51	47.61	46.82
3G Coverage per Market (average across carriers)	49.63	55.10	57.76	58.05
Demographics				
Age	40.60	42.17	40.62	41.89
Household Income	64,537	61,197	60,341	61,292
Household Size	2.55	2.59	2.65	2.40

Notes: This table shows key variables of the U.S. wireless telecommunications market from 2015 to 2018, using consumers data from the Nielsen database and provider characteristics data from the FCC available databases.

Table 9
Summary Statistics - Market Shares and 3G Coverage

	Mean	Std. Dev.	Min	25%	Median	75%	%Zeros	N
Market Share								
Verizon	0.31	0.15	0	0.23	0.29	0.36	7	1470
AT&T	0.33	0.14	0	0.25	0.33	0.40	5	1583
T-Mobile	0.17	0.08	0	0.12	0.18	0.22	25	934
Sprint	0.12	0.10	0	0.04	0.11	0.17	53	588
3G Coverage								
Verizon	80.58	16.11	29.88	71.62	84.18	93.36		
AT&T	91.88	12.84	44.78	89.35	98.61	99.85		
T-Mobile	20.03	20.12	3.25	5.79	14.25	24.96		
Sprint	53.35	23.11	8.77	36.43	53.30	69.66		

Notes: This table shows summary statistics of observed market shares and coverage. Regarding the market shares, the reported data are calculated on the Nielsen Database. Regarding coverage, the data are computed on the 67 DMA markets over a period 2015-2018.

Table 10
Free-riding Evidence

	OLS	OLS
Variable		
Difference in coverage percentages in $t - 1$	0.4333***	0.4914***
Firm fixed-effect	no	yes
Time fixed-effect	no	yes
Market fixed-effect	no	yes
R^2	0.6192	0.9510
Observations	2,454	2,454

Note: This table reports the estimates of Equation1 using the ordinary least squares linear regression.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.

Table 11
Mean Provider-Market-Year Fixed Effects

	Verizon	AT&T	T-Mobile	Sprint
Mean utility (average)	-0.0262 (123/268)	-0.4034 (175/268)	-0.5332 (147/268)	-0.0274 (98/268)
Standard Deviation	0.0483	0.0603	0.0405	0.0452

Notes: The table reports the estimated provider-market-year fixed effects δ_{jmt} in the first stage of the demand model. I report the average mean utilities across years and markets. The number of estimates at 95% significance over total years and the 67 markets are listed in parenthesis.

Table 12

1st Stage parameters estimates - Multinomial Logit

Explanatory Variable	Coefficient	Standard Error
Age * 2G Total Coverage	-0.0536455*	0.0039
Income Group 2 * 2G Total Coverage	-0.2273894*	0.0074
Income Group 3 * 2G Total Coverage	-0.4267435**	0.0023
Income Group 4 * 2G Total Coverage	-0.2645419***	0.0058
Household Size * 2G Total Coverage	0.0903685	0.0007
Age * 2G Total Coverage * GSM	0.0459614	0.0087
Income Group 2 * 2G Total Coverage * GSM	-0.5064160***	0.0063
Income Group 3 * 2G Total Coverage * GSM	0.1307461	0.0014
Income Group 4 * 2G Total Coverage * GSM	-0.2092827**	0.0031
Household Size * 2G Total Coverage * GSM	-0.3785911*	0.0025
Age * 3G Total Coverage	0.0448787 **	0.0021
Income Group 2 * 3G Total Coverage	0.4733281	0.0064
Income Group 3 * 3G Total Coverage	0.0715904**	0.0256
Income Group 4 * 3G Total Coverage	-0.5946649***	0.0199
Household Size * 3G Total Coverage	0.3706929	0.0047
Age * 3G Total Coverage * GSM	0.2662053	0.0067
Income Group 2 * 3G Total Coverage * GSM	0.5108777**	0.0009
Income Group 3 * 3G Total Coverage * GSM	-1.1254515	0.0002
Income Group 4 * 3G Total Coverage * GSM	0.2378637*	0.0004
Household Size * 3G Total Coverage * GSM	0.3536113***	0.0009
Price * Income Group 2	0.0584510***	0.00023
Price * Income Group 3	0.1548299***	0.00049
Price * Income Group 4	0.1538729***	0.00042
Log likelihood	8,632	
Observations	5,568	

Note: The method of estimation is maximum likelihood. Specification is estimated using 1072 provider-market-year fixed effects for the 67 DMA markets. A unit of observation is an available provider, market, and year. The error terms are assumed to follow type-I extreme value distribution. The variance of Verizon σ_V^2 is normalized to 1.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels. See Table 10 in the Appendix for the estimates of the fixed effects.

Table 13

Counterfactual Market Outcomes (Fixed prices and per-unit investment costs)

	Simulated Counterfactual Outcomes			Difference Across Regimes	
	Multiple Standards (I)	Single Standard (GSM)	Single Standard (CDMA)	(GSM-I)	(CDMA-I)
A. PROFIT (\$millions)					
AT&T	3040.49	3096.13	3227.48	+1.83%	+6.15%
T-Mobile	1349.42	1329.45	1312.72	-1.48%	-2.72%
Verizon	3355.78	3407.46	3505.783	+1.54%	+4.47%
Sprint	1284.56	1318.34	1300.75	+2.63%	+1.26%
B. COVERAGE INVESTMENT (%)					
AT&T	98.86	64.30	94.55	-34.96%	-4.36%
T-Mobile	62.53	41.28	45.18	-33.98%	-27.74 %
Verizon	91.58	85.11	88.62	-7.06%	-3.23%
Sprint	75.60	56.68	66.73	-25.02 %	-11.73 %

Notes: This table presents counterfactual market outcomes with: (1) Two incompatible standards, (2) One compatible network deploying GSM standard, and (3) One compatible network deploying CDMA standard when firms can only adjust coverage. Columns (4) and (6) compare outcomes across regimes. The values reported in the table refer to the means across markets.