Uniform vs Competing Standards: A Structural Analysis of the U.S. Wireless Telecommunications Industry*

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Abstract

Different regulations to impose compatibility have prompted fierce debates in a wide range of industries around whether a uniform standard is more beneficial than multiple competing standards because of the ambiguous welfare implications of compatibility. This paper studies the potential impact of unifying two incompatible standards for wireless networks on firms' coverage investment choices, profits, prices, and consumer welfare in the U.S. wireless telecommunications market from 2015 to 2018. I develop and estimate a structural model of consumer choices of wireless carriers and 3G coverage investment to quantify the impact of a compatible network. My model captures two main features of wireless standards. First, since different standards provide different services to consumers, the model allows consumers to prefer one standard. Second, it accounts for the positive network effects among firms under the same standard path. Using counterfactual experiments, I find that a uniform standard is the welfare superior policy, regardless of the technology chosen to unify the wireless network. Whereas the overall producer surplus is higher when moving to uniform wireless networks, not all firms are better off under a uniform network. The counterfactual analysis also underlines a heterogeneous effect of a single standard network on consumers: whether consumers benefit from compatibility depends on the technology chosen. The decline in the consumer surplus under a 3G Universal Mobile Telecommunication System (UMTS) is explained (1) by an increase of the equilibrium prices by two firms that does not compensate for the decline in the network coverages, (2) by customers with existing handsets being stranded with the UMTS standard.

JEL Classification: O3, L1, L2

Keywords: Telecommunication standards, 3G, Investments, Networks, Structural Models

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1 Introduction

The existence of different regulations to impose compatibility raises the question of whether the government should intervene to mandate a uniform standard when firms invest in incompatible products. The heterogeneity in regulating compatibility in a wide range of industries is mirrored in fierce 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, compatibility 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, and they may invest too little under compatibility because private incentives do not internalize positive spillovers (Li, 2017). Despite the growing theoretical literature on compatibility, the effect of a uniform standard on welfare is still an open empirical question. This paper measures the effect of standards on firms' coverage investment choices, firms' profits, prices, and consumer welfare in the U.S. wireless telecommunications industry and evaluates the desirability of a uniform standard relative to alternative competing standards.

Telecommunications are a significant part of the U.S. and world economy, exhibiting fast growth and substantial investments. Understanding the market structure of the wireless telecommunications market is critical to understanding how compatibility may affect firms' incentives and consumers' benefits. Firms collaborate to develop information and telecommunications technologies in the upstream part of this vertical market. The technologies are then used as input to produce intermediate and final goods, such as mobile devices and wireless equipment. Wireless service carriers buy telecommunication equipment to build wireless networks which provide services downstream. The Federal Communication Commission has adopted flexible licensing policies regarding wireless standards. Specifically, mobile service providers have the flexibility to deploy the network technologies and services they choose. In the U.S. market, wireless carriers have aligned themselves behind two incompatible standards for the second and the third generations of wireless networks: the Global System for Mobile Communications (GSM) and the Code Division Multiple Access standards (CDMA) regarding the 2G standards, and the UMTS and the CDMA2000 for the third generation of wireless standards.[1] Incompatibility across wireless standards has been an increasingly focal policy issue since the opposing European Union mandate of a single standard has been recognized as a very successful model. However, the evolution of network technologies has converged on a uniform standard for the fourth generation, LTE, and starting in 2011, all four major U.S. wireless providers have been deploying the LTE technology in their networks.

In the wireless industry, there are two different sources of network effects. On the one hand, networks are

[1] Of the four nationwide wireless providers, AT&T and T-Mobile have deployed technologies on the GSM migration path, while Verizon and Sprint have deployed technologies on the CDMA migration path.

interconnected in that all consumers can communicate with each other, regardless of which standard they are locked into. In other words, the presence of incompatible technology standards does not prevent consumers from benefiting from this source of network effects. On the other hand, by compatibility in this industry, I refer to the ability of wireless interoperability between two wireless networks deploying different standards, and thus 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 prevents network providers that deploy different standards from sharing their networks. Notably, the whole network a consumer has access to is the combined network of the subset of firms deploying the same technology standard. Consumer utilities increase when there is more coverage, and so in larger networks, and vice versa. Therefore, incompatibility in network technologies decreases the network size available to consumers and, thus, the consumers' utilities compared to a compatible network. However, a compatible network, unified under a common standard, might decrease the firms' incentives to invest due to positive spillovers, leading to a smaller network for consumers. These indirect network effects are the focus of this paper.

In this paper, I evaluate the impact of counterfactual compatibility policies on firms' investment choices in network quality, by adjusting the percentage of area with 3G coverage, firms' prices, and consumer surplus. First, I develop and estimate a structural model of consumers' choices of wireless carriers and firms' 3G coverage investment and pricing 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 consumers' choices of handset-carrier bundle and firms' coverage investments, measured by the percentage of the geographical area covered by each carrier, in the U.S. wireless telecommunications market in the period 2015-2018. I use the model and parameter estimates to simulate the firms' coverage investment choices, firms' profits, prices, and consumer welfare, when all carriers adhere to a single standard for wireless networks. I then compare the status quo to the counterfactual market equilibria under a unified UMTS or CDMA2000 network.

Several challenges exist in analyzing how a change to a single standard policy affects market 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. In this setting, since the increase in coverage by a firm affects the coverage available to consumers with a rival provider deploying the same standard, firms may invest less under a unified network due to the benefits derived from the rival's network in providing coverage to its subscribers. 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 a rival deploying the same technology standard. The carrier's coverage becomes a standard coverage from the consumer perspective. Hence, the model captures the positive network effects among firms deploying the same technology standards in their networks. For consumers, 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 two-stage estimation procedure. In the first stage, the demand parameter values are chosen to maximize a likelihood function that includes provider-market-year fixed effects. This identifies the nonlinear demand parameters. To estimate the market-level demand parameters, in the second stage, I decompose the estimated fixed effects, and I use a regression of the estimated effects on price and product characteristics to estimate the observable and unobservable linear parameters.

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. In my model, firms decide on the network quality investment by adjusting the percentage of area with coverage and plan prices to maximize current-period profits. In weighing this decision, they consider that: (i) the increase in coverage by a firm affects the coverage available to consumers with a rival provider using the same standard (positive network externalities), and (ii) the increase in coverage by a firm can lead to consumers switching providers to them and rival providers using the same standard. Besides, the model recognizes different investment costs, depending on the standard deployed in the network. The model builds on Berry et al. (1995), Nevo (2000), Li (2017), 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 standard method of moments techniques. 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 UMTS and the CDMA2000 standard. Since I allow the investment decision to be continuous in coverage, I rely on an iterative algorithm to find the equilibrium coverage for each firm. In particular, I simulate firms playing iterated best-response until no firm has any profitable deviations. I chose the investment cost parameters to match the values of predicted coverage with the observed coverage from the data.

Using parameter estimates from the demand and supply models, I assess the impact of counterfactual compatibility policies in wireless networks. Specifically, I quantify the effects of a uniform standard comparing a compatible network deploying the UMTS technology and a network using the CDMA2000 technology. I employ an iterative algorithm to find the unique firms' simultaneous-move game equilibrium under the two single standard regimes. My framework allows firms to adjust prices and coverages, keeping the per-unit investment costs for UMTS and CDMA2000 coverage fixed. Under a compatible network, both a CDMA2000 and a UMTS standard have higher total welfare. I find that firms do have an incentive to cut back by an average of 20.01% and 9.78% of investment, respectively, under a UMTS and a CDMA2000 uniform standard. Since under a single standard the number of firms with compatible networks increases from 2 to 4, this result shows that the positive network effect dominates when moving to a uniform network. However, the reduction in the coverage under compatibility suggests that firms make excess investments when the government allows for competing standards.[2] Though consumer surplus improves by about \$2.2 billion under a CDMA2000 policy, it decreases by about \$1.7 billion under a UMTS policy.

Even though the overall producer surplus is higher when moving to uniform wireless networks, not all firms are better off. 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. This result also supports a necessary intervention by the government to mandate compatibility, to achieve higher social welfare. Besides, the gains from compatibility are not symmetric nor independent of the technology standard deployed in the market. Whether consumers benefit from compatibility depends on the technology chosen. Two main mechanisms drive the results of the counterfactual analysis. First, under compatibility, consumers lose one dimension of product differentiation, and the decrease in the utility is higher for consumers preferring the CDMA2000 standard in the status quo when the UMTS technology is the chosen standard. Furthermore, the decline in the UMTS coverage investment is not compensated by a decline in the equilibrium prices, which in turn negatively affects the utility for consumers. My results highlight the risk 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 theoretical literature on compatibility predicts that consumers' prices decrease under a compatible network due to fierce competition. However the equilibrium prices increase with the UMTS standard for two major carriers in this market but drop under CDMA2000 in the counterfactual experiments. This result can be rationalized by two related factors: the assumption regarding the initial conditions that the firms inherited at the start of the sample in 2015 and the higher estimated unit investment cost for the UMTS network. First, to evaluate the counterfactual outcomes, I account for the coverage set by the providers in 2015. The network that each carrier has developed until this year, and so the observed coverages in 2015, is the result of strategic interactions affected by the presence of two competing standards in the market and so by two different investment costs. Accounting for the higher drop in coverage by the two UMTS providers under a uniform UMTS network, this result might have been driven by an over-investment by these two providers under multiple standards. Therefore the equilibrium prices set by AT&T and T-Mobile increase as they benefit from larger networks compared to their CDMA2000 competitors. On the other hand, since the firms that deployed the CDMA2000 standard before 2015 paid lower investment costs for their coverage and invested less during that time, they have to ask for lower equilibrium prices under a single standard policy due to more competition intensity.

It is important to recognize that the model has several limitations, in addition to the mentioned shortcomings discussed in the Data and Empirical model sections. First, by the late 1990s, wireless providers had deployed

[2] A social planner counterfactual is required in order to test whether firms over-invest under competing standards.

different incompatible digital technologies in their wireless networks. The choice made in that period could not be changed for the future generations of 2G technologies.[3] I, therefore, study a market characterized by a strong technology multi-path dependency, where the firms' choices of the standard to be deployed in the network were made more than 20 years before the studied period.[4] Second, this paper studies the 3G network investment choices in a period when firms had started investing in the uniform 4G LTE networks. Consumer adoption of wireless providers between 2015 and 2018 was mainly driven by the available 4G coverages, while the 3G network was of secondary consideration for consumers but still of importance. In the period of interest, the goal of wireless providers was to expand 4G coverage. It was, however, necessary to keep 3G networks, as it improved voice service coverage. At that time, many terminals didn't support the voice capability for the 4G LTE networks (VoLTE technologies) yet, so using 3G for the voice was a way to increase coverage.[5] Since the goal of the paper is to study the welfare implication of a uniform standard network relative to incompatible standards, I must focus on the 3G networks, which are based on incompatible technologies. The available data only allows me to study the investment decisions of firms in 3G coverages over the years 2015-2018.[6] Therefore, the counterfactual analysis could be considered reasonably close to the short-term outcome of a uniform standard policy, irrespective of legacy technologies, though the long-term outcome could be considerably different when accounting for the different technological generations the firms deploy.

While providers in the United States are differentiated in UMTS and CDMA2000 providers with respect to the 3G network, where the deployed technologies are built upon two competing standards, all providers are moving towards versions of the 4G uniform LTE technology in the studied years, which is an evolution of the WCDMA technology. The UMTS standard is the 3G wireless standard built on the GSM second-generation technologies based on the WCDMA interface. Even though the working group developing LTE technologies aimed to minimize the impact on the legacy CDMA2000, since LTE has quality advantages relative to the 3G standards, this would imply that the CDMA2000 carriers would have greater marginal improvements relative to their UMTS competitors. This may result in the prediction of the structural analysis being distorted in the long-term.[7] The distortion depends on: (1) how wireless technologies enter into the utility of consumers, though the overall welfare effects are ambiguous given that the effect could either be in the provider network quality coefficients or the carrier fixed effects, (2) the legacy technology chosen by each firm. Since my structural model allows consumers to have preferences over one standard, the structural analysis provides some insights regarding the direction of the effect. If the deployment of LTE technologies improves the efficiency of base stations, and so the

[3] In other words, firms must maintain the chosen standard for all the generations of wireless technologies. Otherwise, changing the wireless standard would require them to change the whole wireless network, thus incurring prohibitive fixed costs.

[4] It is also important to recognize that a lot of institutional and historical detail is necessary to properly study the technological change in this industry and to provide insightful results.

[5] T-Mobile required VoLTE for all phones only starting in January 2021, followed by AT&T, making all terminals, not including VoLTE technologies, incompatible with the providers' networks. By December 2022, Verizon planned to shut down its 3G networks, thus allowing only terminals supporting the VoLTE standards to work on its 4G network.

[6] Even though it would be optimal to study the 3G network investments in the years when 4G technologies were unavailable.

[7] It is important to point out that the scope of this paper is to study the effect of a uniform standard network in the short run, comparing the desirability of a compatible network with respect to a market where there are two competing standards. For this purpose, I develop an agnostic model regarding each firm's technological path and the market's current state where firms have moved to a compatible network. Accounting for the long-term, given the convergence of the US wireless market to a uniform LTE standard, the market outcome and welfare implications might differ from my results. The effect is likely to be affected by the choice made by each firm on the legacy technology concerning its competitors, which is beyond the scope of this project.

quality of a provider's coverage, then the substitution ratio between UMTS and CDMA2000 providers would become more favorable towards the CDMA2000 providers. As I show in the Result section, the cross-coverage elasticities favor the UMTS providers with respect to the CDMA2000 carriers under two competing standards. Thus the LTE technology change would reduce this difference in the long term, conditional on improving the base stations. However, my results also show that consumers prefer the CDMA2000 standard relative to the UMTS, which suggests that there might be some provider-specific characteristics driving the preferences of consumers towards CDMA2000 providers.[8] If the resulting shift of network quality from the LTE technology is driven by provider-specific characteristics, irrespectively of base stations, the substitution patterns would still increase for the CDMA2000 providers with respect to the UMTS firms. Nevertheless, the overall effect remains ambiguous and open to empirical research.

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. In contrast to the previous literature, Sun (2016) treats the investment on base stations as an endogenous product characteristics to study whether coverages set by U.S. wireless providers are strategic complements or substitutes. 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

[8] This intuition is also supported by the higher carrier-fixed effects for CDMA2000 providers reported in Table 3 of the Results section.

station location in response to a government program. Following Sun (2016) and Björkegren (2019), 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 telecommunications 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.

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 positive network externalities 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 firms' coverage investment choices, firms' profits, prices, and welfare under compatible networks. Section 8 concludes.

2 Industry background and data

2.1 The history of wireless standards

The history of standardization in the U.S. wireless telecommunications industry started in the early 1980s when the telecommunication regulation authority, the Federal Communication Commission (FCC), approved the Analog Mobile Phone System (AMPS), also called first-generation (1G) systems, as a common standard to be deployed in the licensed spectrum (Gandal et al., 2003; Fuentelsaz et al., 2008). This was the only spectrum allocation for mobile phone services in the U.S. until 1994. On the contrary, in the EU the regulators chose for a more flexible approach by allowing different standards to be developed and compete in the market. As a result, in the same period, different incompatible systems appeared in Europe.

However, analog systems used the allocated radio spectrum relatively inefficiently, and they supported voice-only calls. When the demand for mobile services started expanding significantly and new services were introduced, especially regarding data transmission, there was unanimous agreement across Europe and the United States about the necessity of changing towards digital technology systems to overcome the limitations imposed by analog systems. The advantages of digital systems over analog technologies are in voice quality, data transmission capabilities, and the level of efficiency in using the frequency spectrum, which allows for supporting more subscribers. [9] 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 afterward, to replace analog systems. With respect to its regulation policy about the first-generation systems, the FCC took a distance from the standard-setting process and let the market determine one or several standards (Gandal et al., 2003). As a result of the market-based approach taken by the telecommunications authority, by the late 1990s, there were two competing standards in the U.S.: CDMA (also known as IS-95A), and GSM. In most cases, coverage was achieved with a combination of re-farmed AMPS frequencies and the new PCS frequencies. It is important to recognize that market forces led to this outcome without any mandate for a common standard nor nationwide roaming (Gandal et al., 2003).

In contrast to the competing standards approach taken by the FCC for the second-generation systems, in Europe, the regulatory authority mandated a single standard, the GSM standard, which would have allowed the European market to cope with the fast-increasing demands for mobile networks. There are two motivations behind the EU's decision regarding the development of a uniform network: it would have ensured inter-state roaming and allowed to exploit greater economies of scale in equipment supply to the benefit of consumers. As a consequence of the regulatory-based approach taken by the EU, the mobile industry experienced faster growth, and the GSM standard became the dominant technology (Gandal et al., 2003), with the main exception of the United States (Fuentelsaz et al., 2008). [10] Indeed, the presence of incompatible networks across the United States made roaming impossible, and the impact on consumers was reflected in choosing the right mobile device. Since different companies used incompatible transmission systems, a phone bought from one company could not work with service from another provider.

As highlighted by Gruber and Verboven (2001) and Gandal et al. (2003), there are advantages and disadvantages to having a uniform standard rather than several competing standards in markets with network externalities. On the one hand, advocates of government intervention argue that adopting a uniform standard allows roaming between different networks, achieving a degree of coverage that could otherwise not be effectively matched by competing standards and product compatibility. The large economies of scale in the production of both network equipment and terminals due to compatibility decrease the unit cost and increase availability, thus decreasing prices for downstream consumers. On the other hand, free market advocates argue that competition among technologies would best guarantee the development of better technological systems and reduce the risk of lock-in an industry in an inferior technology mandated by the government. Another benefit from multiple standards is the higher degree of differentiated products offered since the types of services tend to differ across technologies (Gandal et al., 2003). Nevertheless, in multiple incompatible and fragmented markets, roaming is impossible,

[9] Since frequency spectrum is a limited resource, spectrum efficiency is essential.

[10] In 2002, the US penetration rate hardly reached 50%, while in most European countries was at the 70%. However, it should be pointed out that some researchers not only attribute this delay to the presence of competing technologies but also the pricing policy followed by the EU regulator (Gruber, 1999). It should be pointed out that some authors not only attribute this delay in the US sector to the presence of alternative technologies but also to the pricing policy followed by the regulator (Gruber, 1999). The argument is that the calling party pays system has allowed the EU to consolidate the industry faster.

and network externalities are realized at a lower piece. Moreover, markets characterized by competing standards may also lead to lock-in into inferior outcomes, thereby necessitating government intervention to cope with this network externality (Gruber and Verboven, 2001).

As the mobile market kept growing and the services evolved to more complex and multifunctional features, the industry moved toward a third-generation system (3G), which offered higher frequency spectrum efficiency, vastly improved data transmission rates, multi-media capability, and allowed the possibility of global roaming through the interconnectivity of operators and interoperability across different technologies and among different standard versions.[11] In this context, a new standards battle started between the two leading technologies, and two competing 3G standards were developed: the UMTS and the CDMA2000. There are some differences between the UMTS and the CDMA2000 standards.[12] The CDMA2000 was a direct development of CDMA technology, base on the existing CDMAone infrastructures technologies. Instead, the UMTS was an extension of the GSM path, and thus based on the existing GSM infrastructures technologies, but it used the Wideband Code Division Multiple Access (WCDMA) interface, which was built on the CDMA standard.[13] In other words, the air interface for UMTS was based on WCDMA, which was different from the interfaces GSM employed. While the core networks were the same as in the 2G systems deploying either standard, the migration to 3G networks required major upgrades to the radio interfaces at any rate (Saugstrup and Henten, 2006). However, since the WCDMA interface was essentially incompatible with GSM, the development of network and terminal equipment was not as fast as expected, and providers that had used GSM technology in the second generation networks faced a more difficult challenge as migrating to full 3G capabilities entailed a much more capital intensive overlay network (Tilson and Lyytinen, 2006). This limitation explains in part why UMTS's introduction was delayed in most places (Gandal et al., 2003).[14]

In principle, wireless operators could have chosen to have alternative interfaces on their existing networks. However, the four major providers in the U.S. (and also in Europe) followed the legacy technology migration path as it would have been the less costly alternative. GSM providers opted for the WCDMA interface and thus the UMTS standard, and CDMA 2G providers chose the CDMA2000 path. The primary motivation for this legacy path-dependence is the defined migration path behind the technical specifications, which would have ensured a smoother transition to the 3G networks (Saugstrup and Henten, 2006): the UMTS standard was designed to be backward compatible with existing 2G GSM networks, the CDMA2000 network was backward compatible with its predecessor 2G network.[15]

[11] Roaming between a GSM provider and a CDMA provider is possible through an intermediary that makes the adjustments and translations required by the service.

[12] For technical details of the UMTS and CDMA2000 standards and their differences, see Martínez et al. (2005).

[13] Though 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.

[14] Even though the European Commission mandated the deployment of 3G technologies by the end of 2002, no provider in the European countries met this target deployment date for UMTS, and at the beginning of 2006 GSM was still the dominant technology (Fuentelsaz et al., 2008). However, it should be pointed out that this delay can be attributed to other factors, apart from the incompatibility of the WCDMA interface with the GSM network. Fuentelsaz et al. (2008) provide a detailed explanation of the reasons behind the late deployment of the UMTS technology.

[15] See Funk (1998),Funk and Methe (2001) ,Gandal et al. (2003), Saugstrup and Henten (2006), and Fuentelsaz et al. (2008) for

A key feature of 3G wireless networks built upon incompatible technologies is that they are interconnected in that customers subscribing to any provider can easily make and receive calls from subscribers to other standard networks while using the provider's network. In the U.S. (and several other developed countries), interconnection has been achieved by standard interconnection protocols. In addition, as described above, the third generation mobile standards are backward compatible with the 2G networks, such that intra-standard roaming is possible among different technological versions of a legacy technology. Notably, any UMTS terminal can roam not only on the 3G UMTS network but also still connect to the 2G GSM networks. This also holds for CDMA2000 providers. However, roaming interoperability beyond system boundaries has been a challenging issue (Kim et al., 2003). There have been several efforts by the world's leading wireless organizations (3GPP2 and the GSM Global Roaming Forum) to develop technical solutions that would have allowed for interoperability across different networks and inter-standard roaming.[16] While the telecommunications industry has adopted and promoted inter-standard services, which support seamless roaming on CDMA and GSM systems and enable consumers to use their phones globally, the deployment of interoperable solutions requires major upgrades of the network architecture and changes of network equipment (Kim et al., 2003).

However, as long as different networks are interconnected and coverage is well provided, compatibility across different standards should not be of concern in the wireless telecommunication market. The reason is that if the two networks are not interconnected, the users' benefits from positive network externalities differ significantly across networks, as they can initiate and receive more calls in larger networks. In the case of interconnection, such differences in network effect do not arise (Gandal, 2002; Gandal et al., 2003; Saugstrup and Henten, 2006). However, compatibility matters when the coverage of competing providers differs significantly (Gandal, 2002; Gandal et al., 2003). When networks are compatible, providers can share their networks and a user can make and receive a call by temporarily using another provider's network, regardless of the provider chosen and thus the standard used. On the other hand, in incompatible networks, a provider deploying one technology will benefit from other network providers using the same technology, as their customers can benefit from roaming possibilities only among providers under the same standard path (Saugstrup and Henten, 2006). This can lead to some degree of differences in positive network externalities and thus affect the costumer's choices of providers (Gandal, 2002). Equally, a compatible network may decrease the firms' incentives to invest due to the presence of positive spillovers among firms.

a more detailed discussion of the history of wireless standards worldwide.

[16] The two main technical solutions proposed to allow for inter-standard seamless roaming are based on a gateway solution and a dual-stack solution. See Purnadi and Mandyam (2000), Kim et al. (2003), 3GPP2 (2005) for a detailed explanation of all the standards proposed to allow for intersystem roaming between UMTS and CDMA2000 network.

2.2 The mobile telecommunications 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: mobile voice and 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 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 (FCC, 2013).

Four national wireless carriers in the United States own and control spectrum allocation and wireless networks: AT&T, T-Mobile, Verizon, and Sprint. They are described as nationwide since all offer wireless services to almost all markets in the United States. Verizon leads the market with a market share of more than 35%, compared to 32% for AT&T, 17% for T-Mobile, and 13% for Sprint.[17] Verizon and AT&T are descended from the 1982 breakup of the AT&T telephone monopoly, and they generally have much of the original spectrum allocated in 1982. While Sprint and T-Mobile descend from entrants in the 1995 spectrum auction. The remaining market is split between regional carriers and Mobile Virtual Network Operators (MVNOs), which do not own their base stations but instead rent from the other carriers.

Mobile devices communicate by transmitting radio waves through base stations that act like a transceiver, allowing for both the transmission and reception of radio waves using antennas. When an action is made, the mobile phone sends packets of information to the nearest antenna, which is a part of the provider's base station, that services the carrier chosen by the consumer (or a partner network). Voices and data are transmitted between the handset and the base station through analog or digital signals using a variety of frequency bands. Suppose the receiver of the information is also using a handset. In that case, the packets are rerouted to the nearest base station to the receiver, and the base station will send the information to the receiver. The switching stations transfer information between different base stations (transfer of information between mobile phones), but also between a mobile and a wireline system (calls between mobile and fixed line phones). Further, they also transfer the control for a call between base stations as users move across areas that are controlled by different base stations (handover). Base station controllers manage the allocation of frequencies for each call within a base station.[18] Mobile communication standards define the interfaces between handsets, base stations, and switching stations. As described in subsection 2.1, two different 3G wireless standards have been developed and deployed for mobile communications: the UMTS and the CDMA2000 standards.[19]

[17] The data are from the FCC Communications Market Report, 2018.

[18] The description of how a mobile communication system works is taken from Funk and Methe (2001).

[19] The UMTS and the CDMA2000 are two competing families of 3G mobile communication standards for sending voice, data, and signaling data between mobile phones and base stations. They are defined as mobile cellular systems for networks based on the GSM and CDMA standards, respectively. A complete network system includes the radio access network (UMTS Terrestrial Radio Access Network, or UTRAN, and CDMA2000), the core network (Mobile Application Part, or MAP for WCDMA and ANSI-41 for

The network is distributed over areas called cells, where each cell is allocated at least one base station. The base station is a site where antennas and wireless equipment are placed to create a cell in a wireless network. Therefore, the locations and distances of the base stations set by a carrier define the carrier's wireless network. How providers build their networks affects the quality of mobile voice and data services offered. The signal quality depends on the ability of base stations to create and maintain transmission. 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 transmitting the information. Accordingly, carriers are interested in building base stations to make sure their market areas are well covered, especially where there is a large number of users: the more base stations in an area, the more likely a consumer will be in range to use her handset properly.

However, the choice in the number and location of base stations is constrained by local lands and environmental features. For instance, the presence of mountains in rural areas and skyscrapers in cities can affect the location where carriers can build base stations. The presence of natural and non-natural factors can affect the required power to transmit over more distances, especially when a tall building or a mountain, which can interfere with the base station's effectiveness, must be overcome. Besides, finding enough space to install a base station is often difficult, especially in dense urban or difficult areas. The power requirement and the geographical characteristics of the landscape must be considered when locating stations. Therefore there are idiosyncratic market-specific aspects that affect the network quality by market. These factors are exogenous to the firms and are likely to affect the firms' coverage investment choices homogeneously. In this project, I abstract from the effect of geographical characteristics on the coverage set by each provider.

Aside from geographical features, there are also economic aspects to account for when deciding on the base station set-up. First, the wireless network involves both several end-users and multiple players, both nationwide network providers and MVNOs, who can impose fees and costs on each other by setting roaming agreements. These interactions can affect the incentive faced by firms to improve their coverages, and negotiations among different players may threaten to gridlock (Greenstein, 2020). In the model, I abstract from roaming-related costs and set the cost each provider pays to its roaming partner to zero. Second, although wireless equipment, maintenance, and power costs have lowered over the years, wireless towers must be built in physical space, and sites will be needed for the set-up. The cost of renting or acquiring suitable sites that also comply with the local regulations can be high and can take years.[20] Lastly, this cost is highly affected by the size of the site as well as the location. Notably, individual site costs in downtown areas can be considerably higher than in rural areas. For this analysis, I assume that the market affects the coverage investment decision of firms homogeneously,

CDMA2000), and the authentication of users via SIM (subscriber identity module) cards. The UMTS system adopts the WCDMA direct spread (DS) air interface and has a core network based on the GSM (GSM-MAP) evolutions. The CDMA2000 system adopts the cdma2000 multi-carrier (MC) air interface and is connected to an ANSI-41 signaling protocol in the underlying CDMA2000 networks.

[20] For the large players in the industry, the rates are set via national-level contracts.

regardless of the type and size of the market.

The quality of the network also depends on the technology deployed by the different providers, which can affect both the coverage available to consumers and the data speed. In the United States, firms use two different technologies to encode their signals. AT&T and T-Mobile deploy variants of the GSM standard in their wireless networks, while Verizon and Sprint use the 2G and 3G versions of CDMA technologies in their networks. The two standards differ in some aspects that can affect the effectiveness of base stations across caries as well as the download and upload speeds, depending on the standard deployed. Differences across standards and the versions of the standards available in the carrier's network affect the service quality. Wireless service providers keep upgrading and expanding their existing networks with technologies that enable faster data transfer speeds, which in turn provide 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 (Gandal et al., 2003; Fuentelsaz et al., 2008). Thus, estimation must allow for variation between firms according to the standard used in the wireless network.

The standard deployed by each provider can affect the coverage provided by allowing inter-network roaming across providers under a common standard path. Although wireless carriers primarily offer wireless services using their network facilities, covered areas are often supplemented through roaming agreements, which affects the network quality by improving the coverage available to consumers. From the consumer's point of view, a roaming agreement between two carriers means that when the consumer's phone loses the signal of its wireless provider because of no available network, 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.[21] Providers are incentivized to have roaming agreements with their competitors since, in some areas of the country, low population densities, along with insufficient demand, make it uneconomic for several carriers to build base stations.[22] 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 in the US market. Even if different solutions aimed at providing interoperability and roaming among different standards have been developed and provided in the wireless industry, wireless providers in the US provide automatic roaming to other technologically-compatible providers only. The main reason is that the implementation of the technological solutions that support subscribers roaming between net-

[21]Even 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, customers 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 document *Reexamination of Roaming Obligations of Commercial Mobile Radio Service Providers*, available at https://www.fcc.gov/document/reexamination-roaming-obligations-commercial-mobile-radio-service-0.

[22]FCC document on Reexamination of Roaming Obligations of Commercial Mobile Radio Service Providers

works would require major upgrades in the core network (Kim et al., 2003; 3GPP2, 2005), which might not be profitable for providers in a national market. In the model, I assume consumers are indifferent between the coverage of their provider and rival providers using the same standard.

Besides, subscribers require that the same service features be available wherever they are since they need not know which technology they are using at any given time. Also, subscribers require that the same user interface for supplementary services activation, deactivation, and invocation be provided on the CDMA2000 and UMTS networks (Kim et al., 2003) when migrating or roaming to a different network. It is not straightforward that all data and voice services would work in communications with users on networks based on different technologies (Kim et al., 2003; Saugstrup and Henten, 2006; Martínez et al., 2005).[23] Therefore, AT&T and T-Mobile signed several roaming agreements starting in 2003, which, as a consequence, led to a significant expansion of the GSM network.[24] On the other hand, Sprint signed a roaming agreement with Verizon since they both deploy CDMA technologies and, given Verizon's strength of its expansive coverage network.[25]

In addition, spectrum is another factor affecting the quality of wireless networks. Since the spectrum defines the capacity of information a base station can support, the spectrum owned by each firm is an important driver of the amount of traffic in terms of the number of calls and maximum data speed the firm's network can handle. For instance, as the number of subscribers increases, users can experience lower data transfer when the firm does not hold enough spectrum. Second different parts of the spectrum have better performance in different geographical areas and are owned by different firms. Frequencies under 1000 MHz propagate farther and therefore are more useful in rural areas. Verizon and AT&T own all this spectrum, as this uses the first spectrum licensed to firms. When Sprint and T-Mobile entered the market, most of the low-frequency spectrum had already been appointed. Sprint and T-Mobile might yield less quality from their network than their rivals, especially in rural markets. For the purposes of this analysis, I will abstract from capacity concerns and assume firms hold enough spectrum that has allowed them to invest appropriately in upgrading their base stations to mitigate capacity issues over my sample period.

Lastly, network managers can affect the quality of signals by altering the shape of cells to a certain degree, using technical systems named network management systems. When an action is made in an area in the range of multiple base stations, the network can choose which base station to serve the action. Through careful management, the network can dynamically adjust loads on base stations. Verizon is recognized to have the ability to manage its network efficiently relative to its rivals.

Network providers differ in the service they offer to consumers in terms of coverage and data speed and other

[23] The conditions for setting roaming agreements changed from the uniform 4G LTE technologies onwards.

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

[25] For 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.

dimensions such as customer cares and phone selection. Specifically, phone selection is an important dimension of quality in this industry (Sinkinson, 2014). Table 1 includes grades for network quality in terms of coverage and data speed, reported by Top10Reviews.com.[26] It also reports the grades for the customer care service and the phone selection across network providers. Verizon and T-Mobile have higher rates in the over rate, followed by Sprint and AT&T. This does not reflect the national market share and therefore suggests that other factors rather than the network quality affects the quality of the overall service provided to costumers. Focusing on the network quality dimensions, AT&T and Verizon have the highest grades for coverage and quality at the national level, with T-Mobile and Sprint having substantially worst grades. Overall, the national network quality measures are in line with market shares. However, there is not a linear relationship between spectrum holdings, deployed standards, and quality. Moreover, the providers deploying versions of the CDMA standard are not strictly better than the GSM providers, suggesting that the wireless standard chosen in the network is not pivotal in the signal quality by itself. Rural coverage is worst for each network, which is natural since more sparsely populated areas need more base stations to be similarly effective. The difference is worse for T-Mobile and Sprint, which is consistent with the idea that AT&T and Verizon can effectively serve sparsely populated areas with low-frequency spectrum.

Table 1
2016 Review of Quality

	Verizon	Sprint	AT&T	T-Mobile
Overall Rating	8.03	7.75	7.60	7.85
Coverage and Quality	10	6.50	9.25	6.25
Urban Coverage	A+	B	A	C+
Rural Coverage	A	C-	B+	D-
Speed	A	D	A-	A-
Reliability	A+	B+	A	C+
Flagship Phones	A	A	A+	A-
Midtier Phones	B+	A-	B+	B+
Budget Phones	B	B	B	D
Costumer Service Score	B-	D-	C	B+

Notes: Covers brands reported by Top10Reviews.com in 2016 from the Internet Archive.

For the purpose of this analysis, and since I focus on the short-term effect of compatibility, I have fixed all other service characteristics aside from coverage and the wireless standard deployed by each provider in its network. Thus, phone selection, customer service levels, network management, and spectrum are absorbed in the fixed effects in my model. The rationale behind this methodological assumption is that these features of the service provided are generally hard to change in the short term. Long-term contracts between providers and terminal suppliers determine phone selection. Improvements in customer service require training employees and changes in the management strategy. Changes in network management require changes to the network architecture and replacement of equipment, which can take several years. Spectrum availability only comes with FCC auctions, though there are rare sales or swaps of spectrum by the providers.

[26] How Top10Reviews calculates these grades is not explained, though maps with rating information can be retrieved from RootMetrics' website. This data, however, cannot be scraped and is too large for manual transcription, so I do not conduct a direct analysis of that data.

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 dataset, 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.[27] The dataset reports the handset-carrier bundle chosen, the quantity of handsets 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. In other words, I don't have information about the provider chosen by each consumer, but I observe the pair of mobile phone-voice and data services a consumer subscribes to the selected provider. 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 smartphone 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.[28] 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.[29]

Demographic data. I use the Nielsen Consumer Panel[30] to retrieve demographic information of consumers. Specifically, I use income, household size, and age since they are especially important for taste variation in choosing wireless providers.[31] 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 brackets to construct 4 income groups. To do so, I construct the quartiles from the income brackets and I then assign each household to a group depending on the quartile values. Regarding age,

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

[28] One 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.

[29] Federal Communication Commission, Sixteenth and Seventeenth Reports.

[30] Researcher's own analyses calculated (or derived) based in part on data from Nielsen Consumer LLC and marketing databases provided through the NielsenIQ Datasets at the Kilts Center for Marketing Data Center at The University of Chicago Booth School of Business. The conclusions drawn from the NielsenIQ data are those of the researcher(s) and do not reflect the views of NielsenIQ. NielsenIQ is not responsible for, had no role in, and was not involved in analyzing and preparing the results reported herein.

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

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 U.S. 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.[32]

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.[33]

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 units[34] 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.[35]

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

[32] The 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.

[33] In reality the number of possible plans is large.

[34] An active unit is a subscriber with an active SIM card.

[35] The 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.

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. Regarding the third generation systems, AT&T and T-Mobile followed the GSM technology path and deployed the 3G version of the GSM standard, UMTS, while Verizon and Sprint upgraded their networks deploying the CDMA2000 standard.

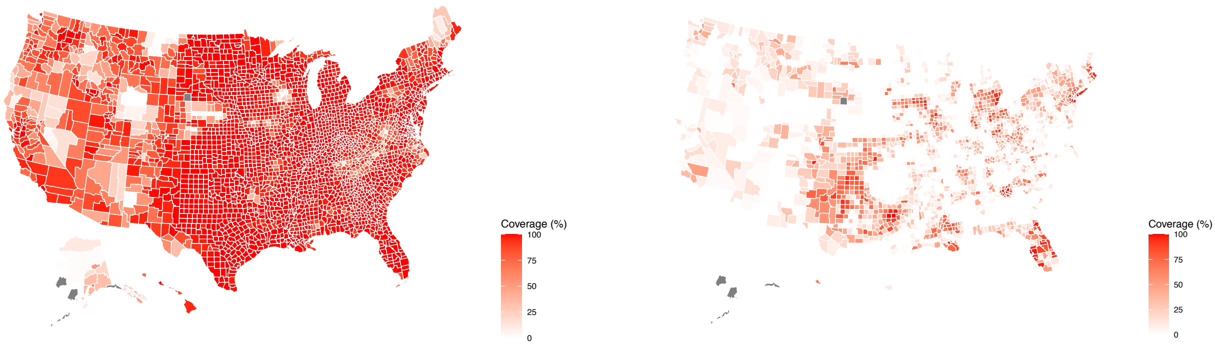
Coverage infrastructure. The coverage is defined as the geographic area covered by the network of a carrier and thus it depends on the number of base stations built in an area/market. The coverage data are created from a database publicly available at the the Federal Communication Commission website at an annual base. 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.[36]

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.[37] I use the Nielsen maps combined with the files provided by the U.S. Census, which collect information about the blocks related to a county, and 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 do not observe 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 GEOIDs[38] 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 UMTS standard (Figure 1) and the two providers deploying the CDMA2000 standard (Figure 2) at the county level.

The resulting data set includes detailed information on consumers and supply choices of wireless service car-

[36]I focus on the 3G technologies since from the 4th generation onwards the wireless technologies became compatible as they were all built upon the WCDMA air interface.
[37]For detailed information of the FIPS classification and a list of county FIPS code see FIPS.
[38]See footnote 32 for a description of GEOID codes.

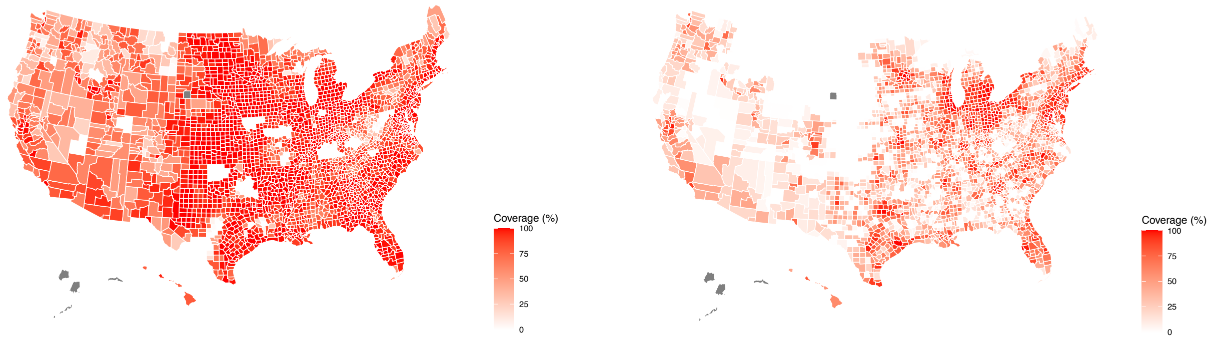


(a) AT&T

(b) T-Mobile

Figure 1

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



(a) Verizon

(b) Sprint

Figure 2

Note: These figures show the 3G CDMA2000 coverage for the 2 nationwide providers as of December 2018, using annual data from the Mobile Deployment Form 477 Databases of the Federal Communications Commission.

riers 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.[39] There are 210 DMAs covering the United States. I collect information on the households' plan purchases for 96 DMAs. I further restrict my sample of DMAs to those whome I observe at least 15 individuals. Since I observe the number of handsets-carriers purchased by each household, I omit those households for which I observe 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 regions[40] 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.

Since the 4 nationwide wireless providers cover more than 97.7% of mobile subscribers in the U.S. in the sample

[39] For more information on the Designed Market Area see DMA maps.

[40] The 67 DMAs correspond to the 70.08% of the whole U.S. population.

period[41], 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 7 and 8 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 benefit from other network provider using the same technology through roaming agreements.

To model the investment decision of firms in coverage, firstly I need to observe variation in the percentage of area with 3G coverage in the sample period. Staring 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 data[42], 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 Reports[43], 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.

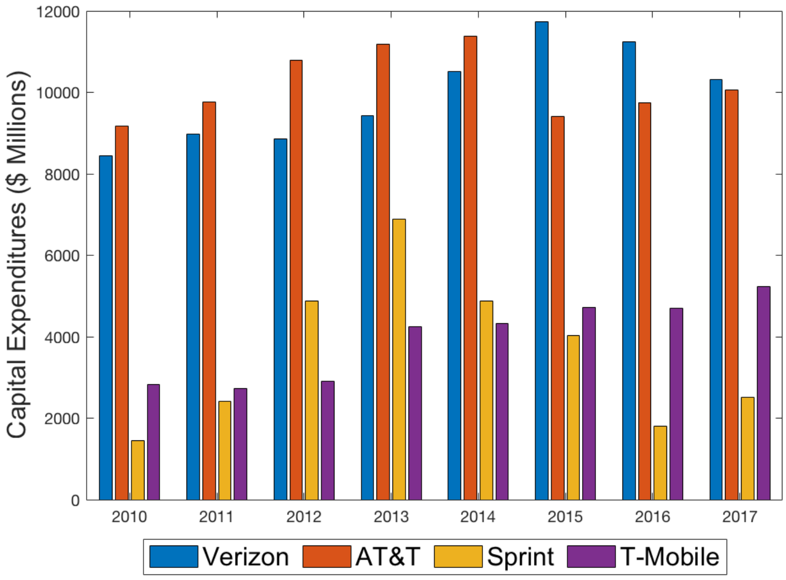
Since the capital investments in the mobile wireless service industry are consistent with the cyclical nature of technological adoption, and since firms started deploying the 4G LTE technologies in their network in 2014, the increase in investments might have driven the upgrading of their networks to the new generation technologies rather than the increase in the network coverage. Figure 4 reports the aggregate coverage available to con-

[41]Datasource: FCC Eleventh to Eighteenth Reports.

[42]CTIA 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."

[43]The 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.

Figure 3
Yearly Capital Expenditures by Provider 2010-2017



Data Sources: FCC Communications Marketplace Report and UBS data.

sumers over time for each wireless 3G standard. As it shown in the figure, both the UMTS and the CDMA2000 providers invested in their coverage in the sample period, suggesting that the share of the capital invested was allocated to expand the provider's network coverage.

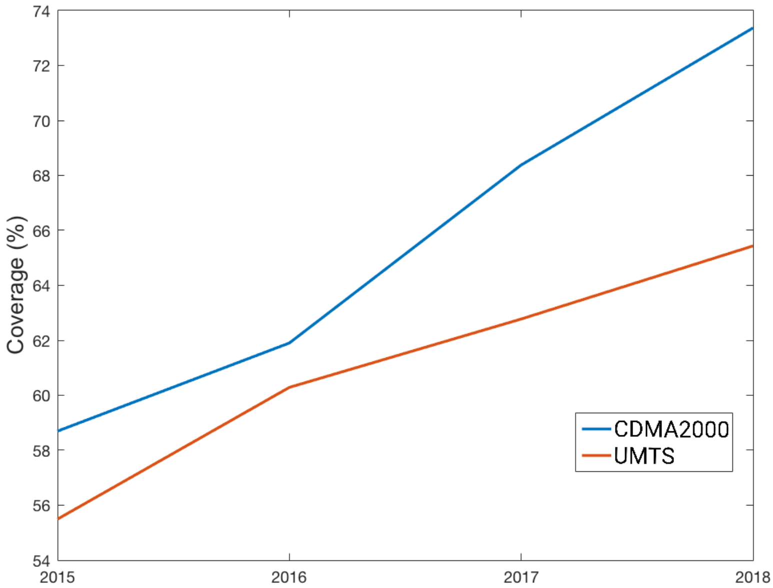
In order to find empirical evidence of a positive network effect across firms deploying the same standard, I estimate the following fixed-effects model at the firm-market-year level:

$$I_{jrmt} = \beta_0 + \beta_1 \max(x^{3G}_{jrm,t-1} - x^{3G}_{krm,t-1}, 0) + \beta_2 \min(x^{3G}_{jrm,t-1} - x^{3G}_{krm,t-1}, 0) + \zeta_{jr} + \eta_t + \kappa_m + \nu_{jrmt} \quad (1)$$

where the dependent variable I_{jrmt} is the additional 3G coverage set by firm j in market m and year t deploying standard r, with respect to the overall coverage set in the previous period. The covariate of interest is the difference between $x^{3G}_{jrm,t-1}$, the percentage of area with 3G coverage by firm j in market m in the previous year $t-1$, and $x^{3G}_{krm,t-1}$ 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 $t-1$. Since the investment incentives may differ when the firm's coverage is greater (lower) than the coverage set by the competitor, I allow for a more flexible specification that accounts for different effects for negative (β_2) and positive (β_1) differences. In addition, I control for unobserved heterogeneity in providers, markets and years, by absorbing a set of fixed-effects. I include in the regression equation the provider , ζ_{jr}, time η_t, and market κ_m fixed effects. ν_{jrmt} is the error term.

The presence of positive spillovers among firms deploying the same standard is captured by β_2. A positive β_2

Figure 4
3G Coverage over Time, by Standard



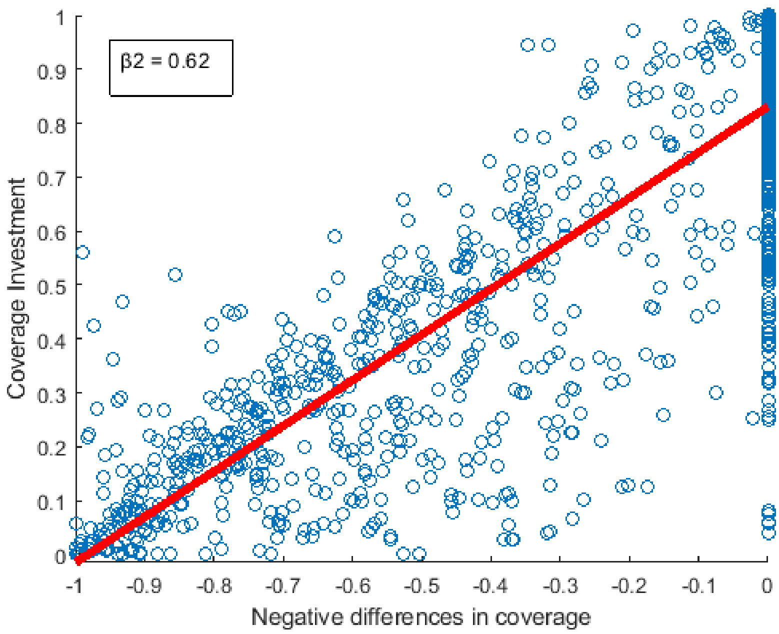
This figure shows the percentage of area with coverage available over time for each wireless standard. It reports the average across DMAs and providers deploying the same standard, using data from the Mobile Deployment Form 477 Databases of the Federal Communications Commission.

provides evidence that firms face fewer incentives to invest in their own network due to positive spillovers from the rival's investment, while a negative β_2 suggests that there is no source of such positive externalities among firms. The idea behind β_2 is that when the coverage set by a competitor is higher compared to the network infrastructure of a provider, and so the term $(x^{3G}_{jrm,t-1} - x^{3G}_{krm,t-1})$ is negative, the provider faces fewer 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 positive network effect, firms with less coverage face higher incentives to invest in future periods in order to reach the network quality offered by the competitor (a negative β_2). In order to provide empirical evidence of positive spillovers among firms deploying the same standard in their network, I expect a positive coefficient from the econometric analysis.

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 negative 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_2 is positive with a magnitude of about 0.6: a one percentage point increase in rival coverage reduces the incentive to invest by 0.6 percentage points, provided the rival has more coverage. This evidence supports the hypothesis of positive network externalities among firms within the same standard path.[44] Another interpretation for a positive β_2 would be that firms are splitting market spaces rather than exploiting the positive spillovers derived from the rival's investment.[45] The coefficient of interest becomes

[44] See Table 9 in the Appendix for details on the regression output.
[45] Augereau et al. (2006) show that internet service providers split evenly across two available 56K modems standards in local markets.

Figure 5
Empirical evidence: Positive Network Externalities



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

positive only when I include the market fixed effects, suggesting that some idiosyncratic market-specific factors correlate with the differences in coverages set by a firm and a rival provider. Even though this result might favor the hypothesis that firms are splitting markets, it might also suggest that there are geographical features that are market-specific, exogenous to all firms, that equally affect and constrain the firms' coverage investment choices.

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 Berry et al. (1995), Goolsbee and Petrin (2004), and Li (2017). In order to simulate the counterfactual market outcome of unifying the wireless network under a common standard, I require a model that can 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 firms' coverage investment choices, firms' profits, prices, 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 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.[46] 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.[47] 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, accounting for on the coverage set by competitors in the current 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 $t = 1, \ldots, 4$, 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 maintain 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 4^{th} 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.

A Designated Market Area m observed in year t defines a market. 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.

[46] Since the majority of DMA regions, according to the Nielsen classification, cover at least one big city or large rural area across the United States, and given the geographical size of those areas, it is reasonable to assume that consumers chose a provider according to the coverage available in the DMA they live. Thus that, coverage in a market does not affect demand in other markets. Even though consumers may want to connect to a person living outside their DMA, it is likely that the coverage available to the connected person has a small effect on the choice of the provider by the consumer. However, it is not possible to estimate the amount of connects an individual has outside the DMA where she lives.

[47] See The mobile telecommunications market subsection 2.2.

2. Consumers realize demand shocks.

3. Consumers choose a network provider to subscribe to, or an outside option, measured by other local facilities-based providers, given existing coverages and prices.[48]

4.1 Demand

Each consumer i in a market chooses one option which is either the outside option $j = 0$ or one of the $j = 1, ..., 4$ 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, deploying standard r, in market m and year t is given as:

$$\begin{aligned} u_{ijrmt} =& \delta_{jrmt} + \sum_{g=2}^{4} \alpha_g p_{jrt} d_{imtg} + \sum_{l=1}^{L} (\gamma_{l2G} + \gamma_{l,2G,GSM} 1_{r=GSM}) x_{rmt}^{2G} z_{imtl} \\ &+ \sum_{l=1}^{L} (\gamma_{l3G} + \gamma_{l,3G,GSM} 1_{r=GSM}) x_{rmt}^{3G} z_{imtl} + \epsilon_{ijrmt} \end{aligned} \tag{2}$$

where the term δ_{jrmt} measures the mean preferences for the product national price p_{jrt}, and the quality of the wireless network provided by a carrier measured by x_{rmt}^{2G} and x_{rmt}^{3G}, common to all consumers in a market, and ϵ_{ijrmt} is a consumer-specific unobserved taste shock consumer i has for carrier j in market m and t. Price sensitivity α_g is allowed to vary by four consumer income levels, with the lowest income group taken as the base, and the dummy variable d_{imtg} equals one if consumer i is in the income group g and zero otherwise.[49] I also include a set of provider-specific characteristics for each of the alternatives in each market x_{rmt}^{2G}, x_{rmt}^{3G}, $1_{r=GSM}$, $1_{r=GSM}$, measured by the 2G and 3G coverages respectively, deploying standard $r \in [GSM, CDMA]$ in each market m and t. For expositional reasons, I define a provider to follow one of the two legacy technologies in this market without distinguishing between the second and third generations of a standard path. I thus group providers deploying the GSM standard in the 2G network and the UMTS standard in the 3G network as deploying the GSM standard and the providers suing the CDMA and the CDMA2000 standards in the 2G and 3G networks as following the CDMA standard migration path.[50] In addition these variables are interacted with L demographic characteristics z_{imtl} - income group, household size, and age of each consumer i - which allow for heterogeneous preferences by demographics.[51] Lastly, the variable $1_{r=GSM}$ equals one when provider j

[48] Since the sum of market shares of other wireless providers is not significant compared to the four nationwide providers, I define the choice of other carriers to be included in the outside option. This decision is supported by the fact that the four nationwide network providers have a cumulative market share of 97.7% on average across the United States between 2015 and 2018.

[49] Following 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, household size, and income. Furthermore, for a theoretical foundation of the price sensitivity to income see Shaked and Sutton (1982).

[50] To interpret the demand parameters in the Result section, I abstract from this common definition, and I distinguish between the 2G and 3G versions of the same standard, as the indicator variable accounts for differences between the GSM and the CDMA standard when interacting with the 2G network coverage. At the same time, it captures the differences between the UMTS and CDMA2000 standards when interacting with the 3G network.

[51] 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.

deploys the GSM standards in its 2G and 3G networks, and zero otherwise. The indicator 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 and among standards versions. Notably, it accounts for the differences in preferences across the GSM and the CDMA standards for 2G coverage. At the same time, it captures differences in the preferences across the UMTS and the CDMA2000 standards regarding the 3G networks.

Following Goolsbee and Petrin (2004), I decompose the mean preferences for each product in each market as a function of price and product characteristics, both observed and unobserved. Consumers derive baseline utility δ_{jrmt} as defined below:

$$\delta_{jrmt} = \alpha_0 p_{jrt} + \gamma_{2G} x^{2G}_{rmt} + \gamma_{3G} x^{3G}_{rmt} + \zeta_{jr} + \xi_{jrmt} \tag{3}$$

The term ξ_{jrmt} 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, and the network management. It is constant across consumers in the same market. The terms x^{2G}_{rmt}, x^{3G}_{rmt} capture the quality of the provider's network in terms of 2G and 3G coverages provided at the standard level r. Since the indicator variable $1_{r=GSM}$ in the individual utility equation does not only capture the technological differences between standards, but they also include other factors that are common across providers within the same technology path, I control for the carrier-specific characteristics in the baseline utility function, including a carrier-specific effect ζ_{jr}. 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.

Let $r \in GSM, CDMA$ be the standard deployed by a firm in its network, and $\mathcal{J}_r = \{j \in \{1, 2, 3, 4\} : j \text{ deploys } r\}$ be the subset of providers in J deploying the same standard r. The coverage available to a consumer choosing provider j which deploys standard r in its network is defined as follows:

$$\begin{aligned} x^{2G}_{rmt} &= \max_{\{j' \in \mathcal{J}_r\}} \{x^{2G}_{jrmt}\} \\ x^{3G}_{rmt} &= \max_{\{j' \in \mathcal{J}_r\}} \{x^{3G}_{jrmt}\} \end{aligned} \tag{4}$$

where x^{2G}_{jrmt} and x^{3G}_{jrmt} are the percentages of the geographical areas covered with the 2G and 3G technologies respectively by provider j in market m in year t. Since I observe the percentages of the geographical area covered by a provider at the block level, I need to aggregate all the blocks included in the same DMA. To do so, I compute the coverage set by a provider in a market-year x_{jmt} as follows:

$$\begin{aligned} x^{2G}_{jrmt} &= N^{2G}_{jrmt} * 100 = \frac{\sum\limits_{c \in C_m} N^{2G}_{cjrmt}}{\sum\limits_{c \in C_m} NTotal_{cmt}} * 100 \\ x^{3G}_{jrmt} &= N^{3G}_{jrmt} * 100 = \frac{\sum\limits_{c \in C_m} N^{3G}_{cjrmt}}{\sum\limits_{c \in C_m} NTotal_{cmt}} * 100 \end{aligned} \tag{5}$$

where N_{cjrmt} is the geographical area in terms of square meters of block c, in the set of blocks $C_m \in m$, covered by provider j respectively deploying the 2G and 3G technologies, $NTotal_{cmt}$ is the overall geographical area in $meters^2$ of block c, such that the terms N^{2G}_{jrmt} and N^{3G}_{jrmt} are a measure of the area-weighted averages of the 2G and 3G coverage of firm j in market m in year t.

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^{2G}_{jrmt} and x^{3G}_{jrmt} measure the coverage infrastructure of firm j deploying 2G technologies as well as the coverage deploying 3G technologies, and $1_{r=GSM}$, captures the average preferences for providers deploying the same technology standard path in their 2G and 3G networks, 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 terms x^{2G}_{jrmt} and x^{3G}_{jrmt} measure the percentage of area with coverage, respectively deploying the 2G and 3G technologies, for a consumer choosing firm j. They distinguish 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. Roaming allows mobile wireless customers to automatically receive service outside the area covered by their provider's network. Mobile wireless service providers enter into roaming agreements with each other so that their customers can roam and receive service automatically, regardless of their location. 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 coverage 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.[52] The carrier's coverage measure becomes a standard coverage measure. By modeling the coverage measure as the maximum value between a provider and a rival's coverage, I assume that a consumer will access a rival's network regardless of any coverage provided by her provider. This means that I might overestimate the positive network effects derived from compatible networks. This is a limitation of my model.

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_{l3G}, $\gamma_{l,3G,GSM}$, and γ_{3G} parameters reflect the positive network effects from firms deploying the same standard[53]: 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. 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 an unrestricted (multivariate normal) covariance matrix will not suffer from the problems related to the logit model. In the case of wireless telecommunication, 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.[54] Therefore, realistic substitution patterns are important to capture the complementarity effect in the coverage investments between firms. For this rea-

[52] Accounting 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 CDMA2000 standard, equals 0.67. Concerning the two providers choosing the UMTS 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 0.69 and 0.23.

[53] I only account for the parameter related to the 3G coverage since in the supply side I endogenize only the investment's choices in 3G coverage by firms.

[54] See Nevo (2000).

son, the consumer-specific unobserved taste shock ϵ_{ijrmt} 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 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.[55]This leads to a utility from purchasing the outside option u_{i0mt} exactly equal to zero.[56]

Consumer i in market m in year t chooses alternative $j = 0, 1, 2, 3, 4$ that maximizes her utility. Assuming that ϵ_{ijrmt} 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, so that consumer i chooses provider j, conditional on $z_{imtl}, x^{2G}_{rmt}, x^{3G}_{rmt}, 1_{r=GSM}, p_{jrt}$ with probability:

$$Pr_{ijrmt} = Pr\left[y_{imt} = j | x^{2G}_{rmt}, x^{3G}_{rmt}, 1_{r=GSM}, p_{jrt}, z_{imtl}\right] = \int_{B_{ijrmt}} dF(e_{imt}), \tag{7}$$

where e_{imt} is the composite error defined in terms of two unobserved components ξ_{jrmt} and ϵ_{ijrmt}, such that $e_{ijrmt} = \xi_{jrmt} + \epsilon_{ijrmt}$, $B_{ijrmt} = \{e_{imt} | u_{ijrmt} > u_{ikrmt} \forall j \neq k\}$, and $F(e_{imt})$ is the density function of this composite error. Then the predicted (by the model) market share of firm j in market m in year t, $s_{jrmt}(p_t, x^{2G}_{rmt}, x^{3G}_{rmt}, 1_{r=GSM}, \xi_{mt}; \theta)$, is computed by the sum over consumers i of Pr_{ijrmt}.

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 the quality of the service provided. This control variable is part of a dynamic model of quality investments that may be driven by the firm's future expectations. However, 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

[55]Following 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:

$$\Omega^* = \begin{bmatrix} \sigma^2_{verizon} & \sigma_{verizon,at\&t} & \sigma_{verizon,t-mobile} & \sigma_{verizon,sprint} \\ & \sigma^2_{at\&t} & \sigma_{at\&t,t-mobile} & \sigma_{at\&t,sprint} \\ & & \sigma^2_{t-mobile} & \sigma_{t-mobile,sprint} \\ & & & \sigma^2_{sprint} \end{bmatrix} \tag{6}$$

[56]I make all the necessary normalization to the outside option. For instance, I set $x_{jrmt} = 0$, $\beta_{0m} = 0$ and the $\xi_{0m} = 0$. This leads to the utility for purchasing the outside option $u_{i0rmt} = \epsilon_{i0}$, but, because of the normalization of the residuals to ϵ_0, this gives $u_{i0rmt} = \epsilon_0 - \epsilon_0 = 0$.

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.[57] 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 approximates the dynamic value function, so that optimization from the static model could approximate a dynamic game.

In each period firms simultaneously decide the coverage-infrastructure investment I_{jrt}, taking into account the coverage already installed by the firm in the previous period and the coverage of its competitors, so the coverage investment choice I_{jrt} is a vector of 67 elements. And, they maximize profits by setting national-level prices for the service provided p_{jrt}[58]. 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_{jrt} of firm j in year t is given by the sum of markups, computed as the difference between prices and marginal costs, over markets times the sum of the consumer's choice probability of adoption of a carrier in a market and year which defines the market share s_{jrmt} of provider j, minus the cost of coverage-infrastructure investment $k(I_{jrt})$:

$$\pi_{jrt} = \sum_{m \in M} (p_{jrt} - mc_{jrmt})\, s_{jrmt}(p_t, x^{2G}_{rmt}, x^{3G}_{rmt}, 1_{r=UMTS}, \xi_{mt}; \theta) A_{mt} - k(I_{jrt}) \tag{8}$$

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

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

$$\begin{cases} \frac{\partial \pi_{jrt}}{\partial p_{jrt}} = \sum_{m \in M} A_{mt} \left[s_{jrmt} + (p_{jrt} - mc_{jrmt}) \frac{\partial s_{jrmt}}{\partial p_{jrt}} \right] = 0 \\ \frac{\partial \pi_{jrt}}{\partial x^{3G}_{jr1t}} = A_{1t} \left(p_{jrt} - mc_{jr1t} \right) \frac{\partial s_{jr1t}}{\partial x^{3G}_{jr1t}} - \frac{\partial k(I_{jrt})}{\partial x^{3G}_{jr1t}} = 0 \\ \vdots \\ \frac{\partial \pi_{jrt}}{\partial x^{3G}_{jrMt}} = A_{Mt} \left(p_{jrt} - mc_{jrMt} \right) \frac{\partial s_{jrMt}}{\partial x^{3G}_{jrMt}} - \frac{\partial k(I_{jrt})}{\partial x^{3G}_{jrMt}} = 0 \end{cases} . \tag{9}$$

[57] In fact, if investment was convex, then firms would want to invest a small amount 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.

[58] Since 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 derivative is the 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 $\frac{\partial s_{jrMt}}{\partial x^{3G}_{jrMt}}$[59]. 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.

Equilibrium This is a game of complete information. A Nash equilibrium of this game is a vector of a firm's coverage investment decision for each market m and $periodt$ for each firm $j = 1, ..., 4$. The first-order conditions reported in equation (9), such that marginal profit from increasing quality equals marginal quality cost, are a necessary condition for any possible Nash equilibria. Moreover, it is necessary to prove that the firm's profit function is concave to ensure that the first-order conditions in equation (9) give the vector that maximizes the profit equation. As shown in subsection 9.1 in the Appendix, the sign of the second-order conditions depends on the cross-partial derivates of the demand function, which is positive in the case of compatible networks. To provide robustness checks in favor of the existence of a unique Nash equilibrium in my structural model, I numerically test whether the simultaneous coverage setting game converges to the same equilibrium at different initial guesses of the cost parameters. The different procedures converge to the same vector of coverage levels, regardless of the starting values, which I take as evidence that a unique equilibrium exists at the estimated model parameters.

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 linear in the percentage of area covered and depends on only the

[59] See subsection 9.1 in the Appendix for a simple model of quality investment.

coverage chosen by the firm itself and not of the competitors' coverage.[60] For firm j, it is given by:

$$k(I_{jrt}) = \sum_{m \in M} [\lambda_1 (x^{3G}_{jrm,t} - x^{3G}_{jrm,t-1}) 1_{j,r=UMTS} + \lambda_2 (x^{3G}_{jrm,t} - x^{3G}_{jrm,t-1}) 1_{j,r=CDMA2000} + \upsilon_{jrmt}] \tag{10}$$

where I_{jrt} is the vector of investments of firm j in each market m, $1_{j,r=UMTS}$ equals 1 if the standard r chosen by firm j is the UMTS standard and, on the other side, $1_{j,r=CDMA2000}$ equals 1 if the standard chosen by the firm $r = CDMA2000$. I, therefore, allow for different coverage investment costs, depending on the 3G standard deployed. This assumption allows me to test in the counterfactuals the effect of a compatibility policy for the UMTS and the CDMA2000 standards respectively. υ_{jrmt} is a specific investment shock unobserved by the firm. It captures factors affecting the cost for coverage that cannot be observed and it is defined as the difference between predicted and observed coverage that makes the equation an identity. I assume firms do not observe the realized shock when they decide on their optimal investments, and the υ_{jrmt} just randomly affects the actual investment from the optimal choice.

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

$$\begin{cases} p_{jrt} = \sum_{m \in M} mc_{jrmt} - \frac{s_{jrmt}}{\frac{\partial s_{jrmt}}{\partial p_{jrt}}} \\ \sum_{m \in M} (p_{jrt} - mc_{jrmt}) \frac{\partial s_{jrmt}}{\partial x^{3G}_{jrmt}} - (\lambda_1 1_{j,r=UMTS} + \lambda_2 1_{j,r=CDMA2000}) = 0 \end{cases} . \tag{11}$$

Since standardization changes the nature of competition among firms turning investment into demand complements [61], the effect of a compatibility policy depends only on the demand ($\frac{\partial s_{jrmt}}{\partial x^{3G}_{jrmt}}$), given that the coverage of competitors does not enter the cost function. [62]

5 Estimation and identification

5.1 Identification

The baseline utility parameters $\alpha_0, \gamma_{2G}, \gamma_{3G}$ 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 $\alpha_g, \gamma_{l2G}, \gamma_{l3G} \gamma_{l,2G,GSM}, \gamma_{l,3G,GSM}, \Omega^*$. Market share variation exists across DMAs and time. So coverage, both for the 2G and 3G technologies, age, and income vary across

[60] It 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.

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

[62] Since 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 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_{jrmt}, 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 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, I argue that prices and coverage are not 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_{jrmt} in the estimation procedure.[63]

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, $\theta_1 = (\alpha_0, \gamma_{2G}, \gamma_{3G})$, and the nonlinear parameters, $\theta_2 = \left(\alpha_g, \gamma_{l2G}, \gamma_{l3G}\gamma_{l,2G,GSM}, \gamma_{l,3G,GSM}, \Omega^*\right)$.

[63] For 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).

It is not straightforward to estimate the structural term ξ_{jrmt} because it is not separately identified from quality in the mean preferences. The standard procedure in demand estimation with market level data, introduced in Berry et al. (1995), requires aggregate market shares, however I observe provider choices at the individual level. I, therefore, exploit the individual-level variation, and I 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, capture all the variation at the carrier-market-year level in a first step, and then the covariates of interest are regressed on these fixed effects in a second step.[64]

In line with Goolsbee and Petrin (2004), in the first stage of the demand estimation, for any candidate values of $\theta_2 = \left(\alpha_g, \gamma_{l2G}, \gamma_{l3G}\gamma_{l,2G,GSM}, \gamma_{l,3G,GSM}, \Omega^*\right)$ and vector of mean preferences δ, I estimate the probability to choose provider j, given by:

$$Pr_{ijrmt} = Pr\left[y_{imt} = j\right] = \int_{C_{ijrmt}} P(\epsilon_{imt})\, d\epsilon_{imt} \tag{12}$$

where $C_{ijrmt} = \{\epsilon_i | u_{ijrmt} > u_{ikrmt} \forall j \neq k\}$ is the set of ϵ_{imt} such that product j provides maximum utility. I compute the probability of choosing provider j by numerically integrating out the multivariate normal errors ϵ_{imt}, conditional on z_{imt} , θ_2, δ. Since the choice probabilities are an integral with no closed form solution, I compute it by using a frequency simulator.[65] I then estimate the parameters θ_2 by maximizing the likelihood function, which includes the product specific dummies in every market[66], over the observed individual choice probabilities. I solve the following objective function:

$$\max_{\theta_2,\delta} \sum_{i=1}^{I} ln(Pr_{ijrmt}(\theta_2, \delta; p_{jrt} x^{2G}_{rmt} x^{3G}_{rmt} 1_{r=GSM} z_{imtl})) \tag{13}$$

This identifies all of the parameters except the ones absorbed in the fixed effects, θ_1. Once the fixed effects δ_{jrmt} 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 baseline utility parameters and the unobservable structural term ξ_{jrmt} 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,

[64] Technically, 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.

[65] I use 4000 draws per consumer.

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

as follows:

$$mc_{jrmt} = p_{jrt} - \frac{1}{\int_i \alpha_i(1 - Pr_{ijrmt})\, dF(d_{imt})} \tag{14}$$

where $F(d_{imt})$ is the cumulative distribution function of consumer types, evaluated at type d_{imt}. 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.[67]

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 υ, for candidate values of λ_1 and λ_2, by using an iterative algorithm to find the equilibrium coverage for each firm. The unobservable term υ 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 υ with the observed coverages x^{3G}_{jrmt} 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 of shocks υ. The variable υ is an unobserved by the firms cost shock that leads the observed investment levels of each firm to differ from their strategies in equilibrium, and therefore it explains the observed differences between the optimal coverages predicted by the model and the observed coverages in the data. 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 the fact that firms can benefit from 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 $x^{3G}(\lambda_1, \lambda_2)_{jrmt}$, the optimal coverage for firm j in each market, at a candidate set of values for θ_{supply}.[68] I then compute the υ respectively for the UMTS and the CDMA2000 technologies, as the difference between observed 3G coverage and the coverage predicted by the model.

In a second step, I use the computed υ and the equilibrium coverage for each carrier to calculate the moments,

[67] Specifically 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.

[68] The 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.

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 $\mathbb{E}\left[x^{3G}(\lambda_1,\lambda_2)_{jrmt}\upsilon(\theta_{supply})\right]=0$, respectively for the UMTS and the CDMA2000 standard, to match the moments of the model with the moments computed from the data. Through the GMM estimation, the vector of parameters θ_{supply} is chosen to make the values of predicted x^{3G}_{jrmt} match the observed coverage from the data.

Table 2
1^{st} Stage parameters estimates

	Coefficient	Standard Error
Explanatory Variable		
Age * 2G Total Coverage	-0.033	0.005
Income Group 2 * 2G Total Coverage	-0.261**	0.005
Income Group 3 * 2G Total Coverage	-0.659**	0.006
Income Group 4 * 2G Total Coverage	-0.265***	0.007
Household Size * 2G Total Coverage	0.313*	0.001
Age * 2G Total Coverage * GSM	0.046	0.005
Income Group 2 * 2G Total Coverage * GSM	-0.406***	0.008
Income Group 3 * 2G Total Coverage * GSM	0.431	0.003
Income Group 4 * 2G Total Coverage * GSM	-0.042*	0.003
Household Size * 2G Total Coverage * GSM	-0.316*	0.003
Age * 3G Total Coverage	0.029 *	0.002
Income Group 2 * 3G Total Coverage	-0.012***	0.006
Income Group 3 * 3G Total Coverage	0.071***	0.024
Income Group 4 * 3G Total Coverage	-0.220***	0.021
Household Size * 3G Total Coverage	-0.228*	0.005
Age * 3G Total Coverage * UMTS	-0.049	0.004
Income Group 2 * 3G Total Coverage * UMTS	0.323**	0.001
Income Group 3 * 3G Total Coverage * UMTS	-0.266	0.000
Income Group 4 * 3G Total Coverage * UMTS	0.327**	0.000
Household Size * 3G Total Coverage * UMTS	0.354**	0.001
Price * Income Group 2	0.059***	0.000
Price * Income Group 3	0.155***	0.001
Price * Income Group 4	0.154***	0.001
Multivariate normal		
$\sigma_{verizon,at\&t}$	1.311	0.002
$\sigma_{verizon,t-mobile}$	0.229	0.001
$\sigma_{verizon,sprint}$	1.765	0.002
$\sigma_{at\&t,t-mobile}$	1.037	0.002
$\sigma_{at\&t,sprint}$	0.578	0.001
$\sigma_{t-mobile,sprint}$	0.016	0.002
$\sigma^2_{at\&t}$	2.212	0.005
$\sigma^2_{t-mobile}$	2.412	0.001
σ^2_{sprint}	0.151	0.002
Log likelihood	8,4288	
Observations	5,568	

Note: The method of estimation is maximum likelihood. Specification is estimated using 1,072 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 the multivariate normal distribution. The variance of Verizon $\sigma^2_{verizon}$ 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. Standard errors are corrected to control for sampling error due to data at different levels of aggregation used in the two-stage estimation.

6 Results

The estimated coefficients for the key parameters in stage 1 are reported in Table 2.[69] 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 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.[70]

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 expectations. The four price coefficients imply that higher income groups are less sensitive to price than lower groups. [71] All else equal, consumers prefer the CDMA technologies when accounting for the overall coverage. Decomposing the network into 3G and 2G technologies, consumers get greater utility from the GSM network deploying 3G UMTS 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 UMTS technology compared to other groups. One explanation for this could be the differences between the UMTS and the CDMA2000 standards. 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 2G GSM and 3G UMTS technologies close to zero. However, higher age is associated with higher utility from the second and third generation of the GSM and UMTS standards. Lastly, increases in the household size are associated with increases in the utility of the CDMA relative to the GSM technology, even though larger families prefer the GSM technology standard when accounting for the 3G UMTS technology only.[72]

[69] As a robustness check, I estimate my model with multivariate logit. Table 11 reports the estimated parameters. As expected, the results are similar to those in Table 2.

[70] The fixed effects are too numerous to be reported completely. For expositional reasons, I report them in the Appendix. Instead of reporting all the 1,072 estimates and standard errors, I report in Table 10 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.

[71] Since 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.

[72] Due 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 7, 8, and 9 in the subsection Figures and Tables in the Appendix.

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.[73]

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. [74] On the other hand, older people seem to be less sensitive to 3G coverage.[75]

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, γ_{2G}, and γ_{3G}. 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 baseline utility δ_{jrmt}. Consumers like higher 3G coverage but they dislike 2G technologies.[76] Nevertheless, the baseline 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 CDMA2000 standard in its network is associated with a higher utility on average with respect to the providers using the UMTS standard, given higher fixed effects for Sprint and Verizon. A possible explanation for this is related to the period of analysis and the

[73] The procedure to measure the sensitivity to 2G coverage for each income group is the same as explained for the price coefficients. See footnote 67.

[74] The procedure to measure the sensitivity to 3G coverage for each income group is the same as explained for the price coefficients. See footnote 67.

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

[76] The 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.

technological characteristics of the UMTS 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 CDMA2000 technologies allow for better data speed, it is reasonable to assume that consumers on average prefer the CDMA2000 standard.

Table 3
2^{nd} Stage estimates from fixed effects regression

	Coefficient	Standard Error
Explanatory Variable		
AT&T	0.278	0.401
T-Mobile	0.147	0.400
Sprint	0.698*	0.396
2G Total Coverage	-0.105***	0.016
3G Total Coverage	0.297***	0.028
Price	-0.263***	0.063
R2	0.781	
Observations	1,072	

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.

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 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%).

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

Table 4
Mean Quality Elasticities

	1 % change in network quality			
	AT&T	T-Mobile	Verizon	Sprint
Change of Market Share				
AT&T	1.396	0.579	-0.089	-0.099
T-Mobile	0.280	1.655	-0.040	-0.043
Verizon	-0.409	-0.413	0.243	0.069
Sprint	-0.293	-0.282	0.049	0.286

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.

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.[77]

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 smaller cross elasticities with all other carriers. Sprint provides less baseline utility to its consumers, as reported in Table 10 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.

Focusing on the cross-elasticities by pair of providers according to the standard deployed by each pair, the demand for the UMTS providers is less elastic when their CDMA2000 rivals increase the network quality, by increasing coverage, compared to the elasticity of the demand for CDMA2000 providers with respect to the network quality when a GSM provider raises its coverage. Notably, more consumers substitute away from Verizon and Sprint when AT&T or T-Mobile increases quality than vice versa - this varies between -0.10% to -0.04% between the two UMTS providers when Verizon and Sprint increase their coverage compared to a variation between -0.41% and -0.29% for Verizon and Sprint for an increase in coverage by AT&T and T-Mobile. Moreover, Verizon and Sprint have a smaller own effect than their UMTS rivals. These results suggest that while AT&T and T-Mobile are more competitive on the network quality in terms of coverage provided to consumers, Verizon and Sprint offer better services in terms of unobserved quality. Given the low baseline utilities related to Verizon and Sprint, as reported in Table 10 in the Appendix, consumers who selected the two carriers must have gotten a large idiosyncratic taste shock. As a result, substitutes away from these firms are the lowest when rivals increase quality.

Table 5 reports the resulting estimates for the supply side. I use the demand estimates and the price first-order

[77] This 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.

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

Variable	Mean	Std. Err.			
Own-Price Elasticity	-2.83	0.01			
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

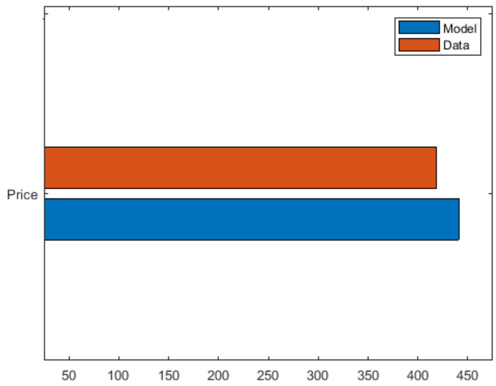
Note: This table reports price elasticities, per-unit coverage investment costs, prices, and consumers marginal costs calculated from the two-stages demand estimates from Table 2 and Table 3 combined with first-order conditions of the firms' profit function.

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. UMTS technologies are estimated to be more costly compared to the CDMA2000 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 UMTS carriers while it costs $8,230 for CDMA2000 firms on average across all markets. 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.[78] Taking into account the total estimated costs of building a base station by the engineering papers (Johansson et al., 2004; Claussen et al., 2008; Björkegren, 2019), an increase of 1% point of coverage costs around $16,000.[79] 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.

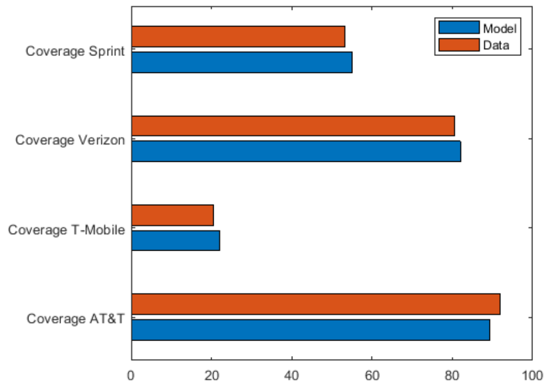
Figure 6 shows the moments in the model and in the data, regarding prices (left graph) and coverages (right graph). Comparing the predicted and the observed prices and coverages across providers, it can be inferred

[78] For a detailed explanation of how I compute the base station-related coverage see subsection 9.2 in the Appendix.

[79] Claussen et al. (2008) estimate a cost of $ 285,000 for 15 years, while Johansson et al. (2004) find a cost of $ 266,000 for macro base stations.



(a) Model fit - Prices



(b) Model fit - Coverages

Figure 6

These figures report the first moments of price (left) and coverage (right). They compare the aggregated moments predicted by the model with the moments calculated from the observed data

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 UMTS standard is the wireless standard deployed in the wireless network, and I evaluate how firms adjust their coverage investment under the UMTS cost. In a second step, I assess how a compatible network under the CDMA2000 technology affects the coverage investment of firms. Finally, I evaluate and compare the two compatibility policies with the status quo, in terms of firms' coverage investment choices, firms' profits, prices, and consumer welfare. 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.

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 iterative 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 $(\mathbf{p}, \mathbf{x^{3G}})$. 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 $p^{h+1} = mc + \rho^{-1} s(p^h, x^{3G,h})$.[80]

2. Update market shares and elasticities with p^{h+1} and $x^{3G,h}$

3. Use the FOC to compute $x^{3G,h+1}$, 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 $x^{3G,h+1}$ for each carrier.

4. Update market shares with p^{h+1} and $x^{3G,h+1}$

5. Let $d_{max} = \max(d_p^h, d_{x^{3G}}^h)$, where $d_p^h = \max|p^{h+1} - p^h|$ and $d_{x^{3G}}^h = \max|x^{3G,h+1} - x^{3G,h}|$

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 $(\mathbf{p^{h+1}}, \mathbf{x^{3G,h+1}})$ 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 my initial conditions. 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 UMTS and the CDMA2000 standard, which gives evidence that rules out multiple equilibria.[81]

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 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 UMTS 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.[82] The precise nature of the selection

[80] Where ρ defines the ownership structure.

[81] I 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 12 in the Appendix.

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

process, as well as the related costs and benefits, is outside the purpose of this project.[83] 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 Williams (1977) and Small and Rosen (1981). 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 UMTS and the CDMA2000 compatible network.

Table 6 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 unified UMTS standard network, and (3) a unified CDMA2000 standard network. Under a compatibility policy, both a UMTS network and a CDMA2000 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 UMTS standard and by \$8.4 billion under the CDMA2000 standard. However, not all firms are better off under compatibility. T-Mobile loses profits deploying the UMTS standard because it loses one dimension of product differentiation. Besides, a UMTS network results in about \$1.77 billion lower consumer surplus than under networks using multiple standards. On the contrary, a network deploying only the CDMA2000 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 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 UMTS standard and 9.78% less under CDMA2000[84]. The high difference between the two compatibility regimes can be explained by the higher per-unit investment cost firms pay for the UMTS coverage,

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

[84] For a graphical visualization of the comparison of the coverage set by each provider under each scenario see Figure 10 in the subsection Figures and Tables in the Appendix.

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.[85]

The annual average price increases for the two providers deploying the UMTS standard in the status quo and it decreases for Verizon and Sprint in the UMTS network. It decreases for all four nationwide network providers under the CDMA2000 technology standard. One explanation for the increase in the price of AT&T and T-Mobile with a compatible UMTS 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 UMTS 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 coverage set in the years before 2015 in contrast to the 2 CDMA2000 providers. Therefore, in the case of a single standard scenario, the equilibrium prices for those firms increase as they benefit from the more extensive networks set in the years before 2015. This explanation is also supported by the cross-coverage elasticities estimated in Table 4. The loss in the market share by AT&T and T-Mobile when the CDMA2000 competitors increase their coverage is lower compared to the loss by Verizon and Sprint for an increase in the coverage investment by AT&T and T-Mobile. These results suggest that the demand for the two UMTS carriers is more elastic in coverage. On the other hand, since the firms that deployed the CDMA2000 standard before 2015 paid lower investment costs for their coverage and invested less during that time, they have to ask for lower equilibrium prices under a single standard policy.[86]

The analysis highlights two mechanisms in the market for wireless services, which depend on the technology to deploy in the network. Under the UMTS regime, firms face higher investment costs, and therefore they have incentives to invest less in the UMTS network compared to the CDMA2000 scenario. The decrease in the firm's coverage investment under the UMTS standard is twice as much as the decrease in the investment under the CDMA2000 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 CDMA2000 standard in the status quo might lose more utility when they are locked into the UMTS standard compared to the loss in the utility measure of consumers who choose the UMTS standard when the CDMA2000 technology is the standard deployed in the compatible network. Under UMTS compatibility consumers are worst off, even if the resulting total surplus is higher.

[85] The lower incentive faced by the firms due to a higher investment cost for the UMTS technologies compared to the CDMA2000 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.

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

Table 6
Counterfactual Market Outcomes

	Simulated Counterfactual Outcomes			Difference Across Regimes	
	Competing Standards (I)	Uniform Standard (UMTS)	Uniform Standard (CDMA2000)	(UMTS-I)	(CDMA2000-I)
A. SOCIAL WELFARE ($millions)					
∆Social Welfare	-	-	-	+2227.1	+8433.4
∆Consumer Surplus	-	-	-	-1765.7	+2186.4
∆Producer Surplus	-	-	-	+4149.8	+6246.9
Profits					
AT&T	3040.49	3180.66	3267.31	+4.61%	+7.46%
T-Mobile	1349.42	1200.98	1411.09	-11.00%	+4.57%
Verizon	3355.78	3572.56	3647.40	+6.46%	+8.69%
Sprint	1284.56	1358.04	1451.04	+5.72%	+12.96%
B. COVERAGE (%)					
AT&T	98.86	64.35	88.04	-34.91%	-10.94%
T-Mobile	62.53	42.50	50.92	-32.03%	-18.56 %
Verizon	91.58	88.50	89.77	-3.36%	-1.98%
Sprint	75.60	68.24	69.81	-9.73 %	-7.66 %
C. ANNUAL PRICE ($)					
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) unified UMTS standard network, and (3) unified CDMA2000 standard network. Columns (4) and (5) compare outcomes across regimes. The values reported in the table refer to the means across markets and years.

8 Conclusion

In this paper, I study the firms' investment decisions in a market where there are underlying 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 earned by some firms, in the counterfactual analysis, 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 in order to achieve higher social welfare. 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 since mandating standards might lock in an industry in a standard (Farrell and Saloner, 1985) that leads to lower consumer welfare.

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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 x for a single product offered to final consumers in one market. The firm j's profit maximization problem is given by:

$$\max_{p_j, x_j} \pi_j = (p_j - mc_j)\, s_j(p, x, \xi; \theta_2) - I(x_j) \tag{15}$$

where p_j and x_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 $I(x_j)$ is the function of the cost of firm j to provide coverage x (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, that all consumers buy regardless of prices, and that the market population is normalized to 1.

The FOCs for firm 1 are then given by:

$$\begin{aligned} \pi_{1p_1} &= s_1(p, x, \xi; \theta_2) + (p_1 - mc_1)\,\frac{\partial s_1}{\partial p_1} = 0 \\ \pi_{1x_1} &= (p_1 - mc_1)\,\frac{\partial s_1}{\partial x_1} - \frac{\partial I(x_1)}{\partial x_1} = 0 \end{aligned} \tag{16}$$

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 x_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:

$$\begin{bmatrix} \frac{\partial p_1}{\partial x_2} \\ \frac{\partial x_1}{\partial x_2} \end{bmatrix} = \begin{bmatrix} \frac{\partial^2 \pi_1}{\partial p_1 \partial p_1} & \frac{\partial^2 \pi_1}{\partial p_1 \partial x_1} \\ \frac{\partial^2 \pi_1}{\partial p_1 \partial x_1} & \frac{\partial^2 \pi_1}{\partial x_1 \partial x_1} \end{bmatrix} \begin{bmatrix} -\frac{\partial^2 \pi_1}{\partial p_1 \partial x_2} \\ -\frac{\partial^2 \pi_1}{\partial x_1 \partial x_2} \end{bmatrix} \tag{17}$$

Where

$$\begin{aligned} \pi_{pp} &= 2\frac{\partial s_1}{\partial p_1} + (p_1 - mc_1)\frac{\partial^2 s_1}{\partial p_1 \partial p_1} \\ \pi_{px_1} &= \frac{\partial s_1}{\partial x_1} + (p_1 - mc_1)\frac{\partial^2 s_1}{\partial p_1 \partial x_1} \\ \pi_{x_1x_1} &= (p_1 - mc_1)\frac{\partial^2 s_1}{\partial x_1 \partial x_1} - \frac{\partial^2 c_1}{\partial x_1 \partial x_1} \\ \pi_{x_1x_2} &= (p_1 - mc_1)\frac{\partial^2 s_1}{\partial x_1 \partial x_2} \\ \pi_{px_2} &= \frac{\partial s_1}{\partial x_2} + (p_1 - mc_1)\frac{\partial^2 s_1}{\partial p_1 \partial x_2} \end{aligned} \tag{18}$$

This gives

$$\begin{aligned} \frac{\partial p_1}{\partial x_2} &= \frac{1}{\pi_{pp}\pi_{x_1x_1} - \pi_{px_1}^2}\left(\pi_{px_1}\pi_{x_2x_1} - \pi_{x_1x_1}\pi_{px_2}\right) \\ \frac{\partial x_1}{\partial x_2} &= \frac{1}{\pi_{pp}\pi_{x_1x_1} - \pi_{px_1}^2}\left(\pi_{px_1}\pi_{x_2x_1} - \pi_{pp}\pi_{x_1x_2}\right) \end{aligned} \tag{19}$$

Note that the second-order conditions require $\pi_{pp} < 0$ and $\pi_{x_1x_1} < 0$ 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 $\frac{\partial x_1}{\partial x_2}$) depends on whether p and x_1 are strategic complements or substitute and, most important, whether we are in a compatible or incompatible market: if there is compatibility then x_1 and x_2 are complements and $\pi_{x_1x_2} > 0$ 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 $\frac{\partial^2 s_1}{\partial x_1 \partial x_2}$ 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.

How far a signal ca go from a tower depends on several factors such as the geographical configuration of the market and the technology standard deployed. Since I don’t observe any information regarding the specific geographical characteristics and the number of towers build in a specific market, 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.

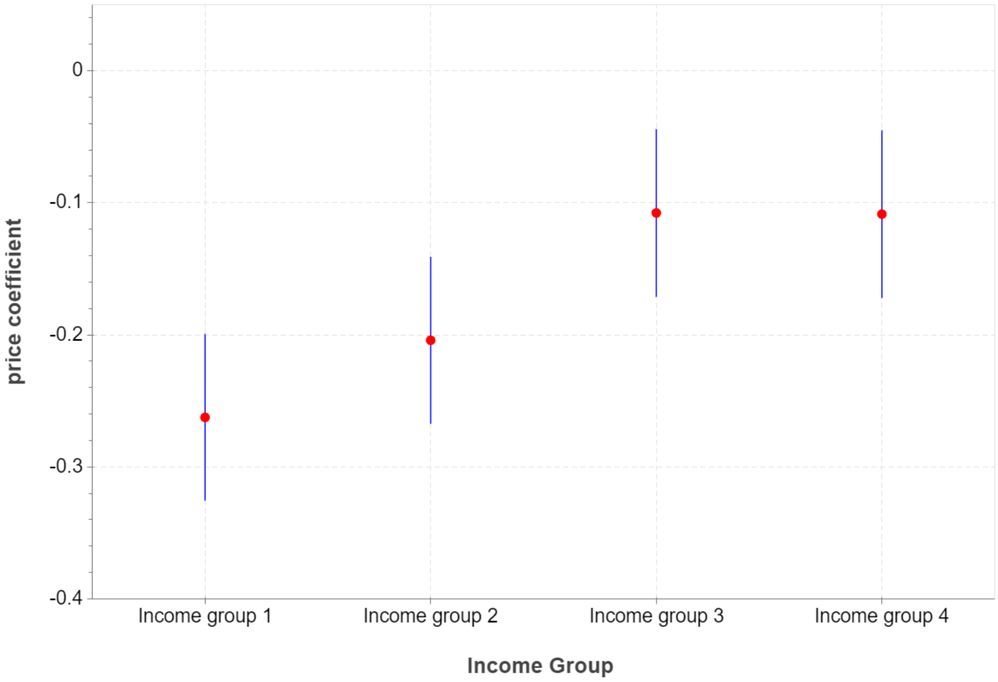
Since hexagons are regular geometrical figures, to determine the area covered by a base stations I can divide each hexagon into 12 similar right triangles with base of length a, height of length $b = \sqrt{3}2a$ and side $c = 2a$. According to engineers and industry experts, the maximum distance the signal ca 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:

$$Area_{abc} = \frac{a * b}{2} = \frac{27 * 46.77}{2} = 631.39km^2 \tag{20}$$

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 than taking the mean. I obtain that a new base station leads to a constant increase in coverage of 17.5% across markets on average.

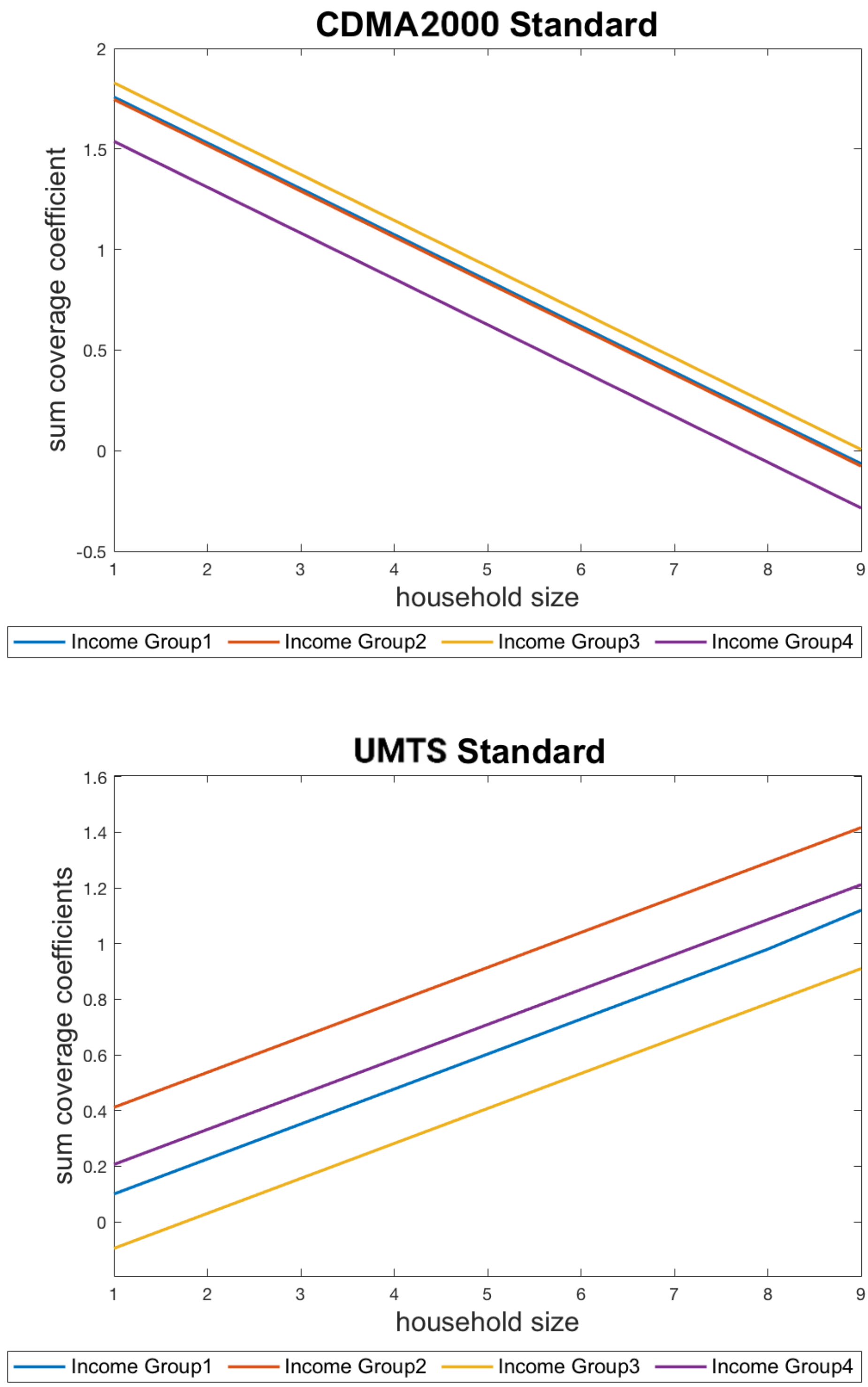
9.3 Figures and Tables

Figure 7
Demand model results: price effect by income group



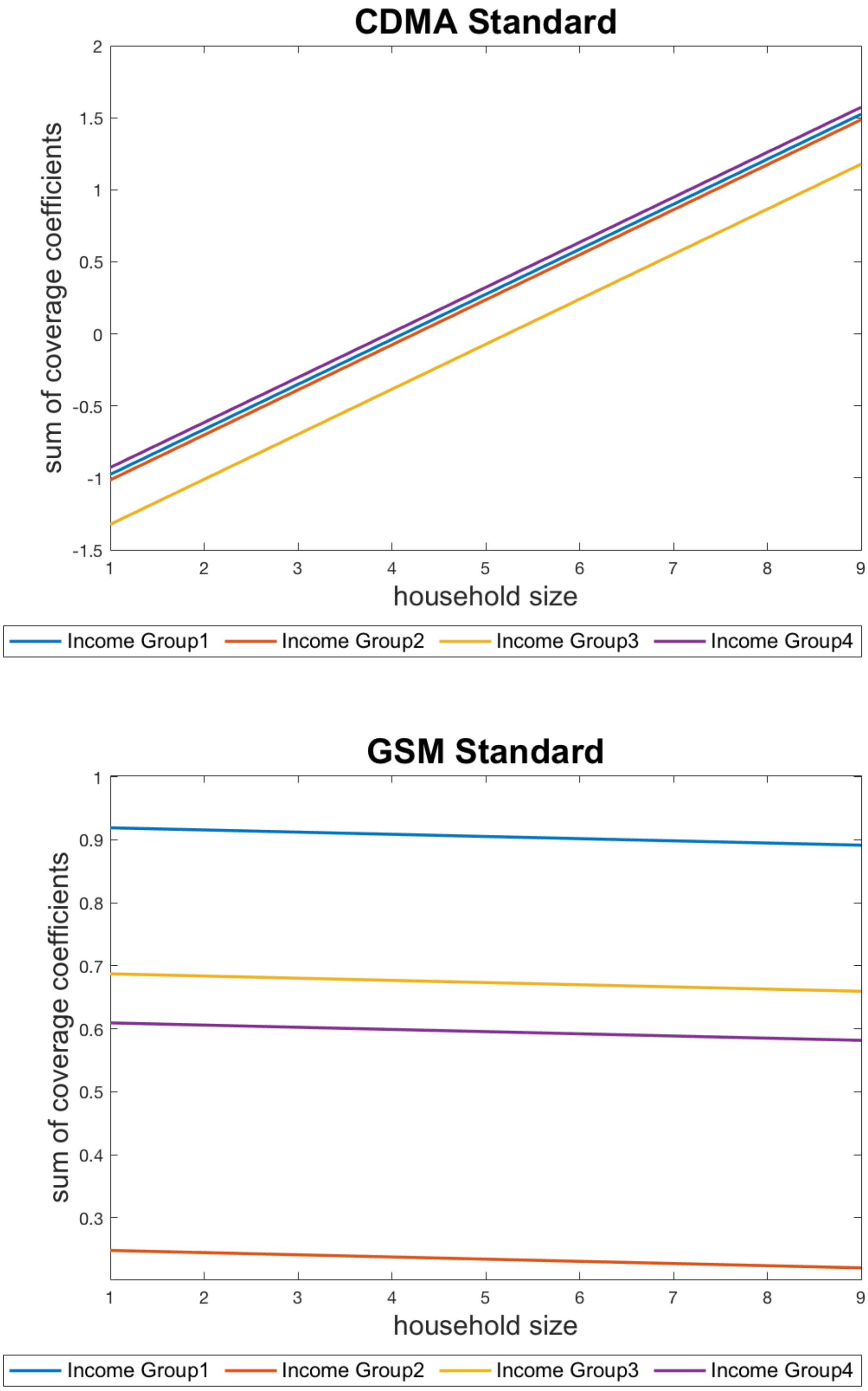
This figure plots the price coefficients across income groups, aggregating the price coefficients estimated in the first and in the second stage of the demand model. The vertical lines report the standard errors.

Figure 8
Demand model results: 3G coverage effect by income group



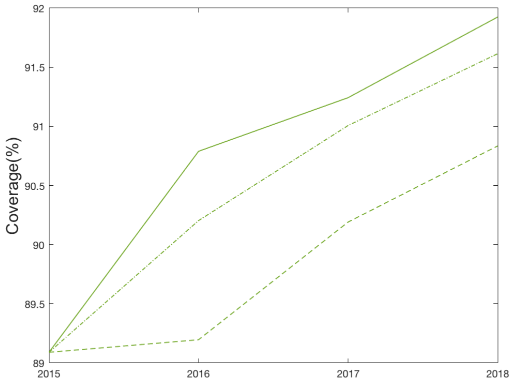
These figures plot the 3G coverage coefficients from the first and the second stages of the demand model across income groups. They compare the preferences for CDMA2000 and UMTS standard. Age is held fixed, while household size is allowed to vary across individuals.

Figure 9
Demand model results: 2G coverage effect by income group

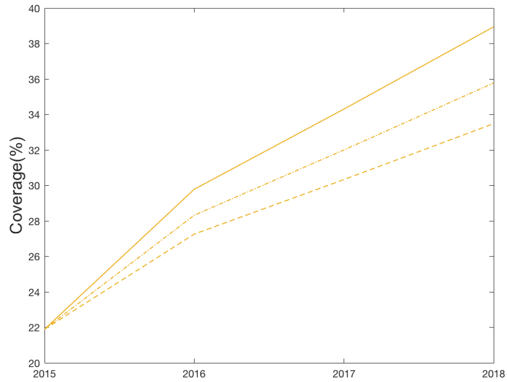


These figures plot the 2G coverage coefficients from the first and the second stages of the demand model, across income groups. They compare the preferences for CDMA and GSM standards. Age is held fixed, while the household size is allowed to vary across individuals.

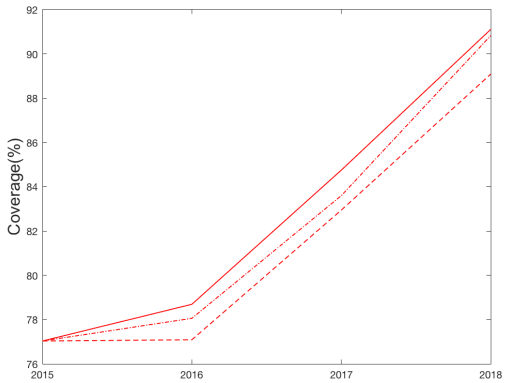
Figure 10
Counterfactual 3G Coverage under Compatibility



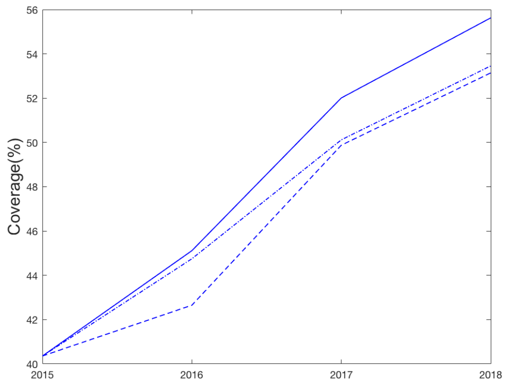
(a) AT&T



(b) T-Mobile



(c) Verizon



(d) Sprint

These figures show 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 UMTS, and the dash-dotted lines are the counterfactual coverage for CDMA2000.

Table 7
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

Note: 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 8
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		

Note: 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 the period 2015-2018.

Table 9
Positive Network Externalities - Evidence

	OLS	OLS	OLS	OLS
Variable				
Difference in coverage percentages in $t-1$ for $x_{jmt} > x_{kmt}$	1.301***	0.930***	0.384***	0.387***
Difference in coverage percentages in $t-1$ for $x_{jmt} < x_{kmt}$	-0.359*	-0.0152	0.670***	0.619***
Time fixed-effect	no	yes	no	yes
Firm fixed-effect	no	no	yes	yes
Market fixed-effect	no	no	yes	yes
R^2	0.126	0.104	0.974	0.957
Observations	1,164	1,164	1,164	1,164

Note: This table reports the estimates of Equation1 using the ordinary least squares linear regression. The dependent variable is the additional 3G coverage set by the firm in market m and year t, with respect to the overall coverage set in the previous period. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.

Table 10
Mean Provider-Market-Year Fixed Effects

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

Note: 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 11
1^{st} Stage parameters estimates - Multinomial Logit

	Coefficient	Standard Error
Explanatory Variable		
Age * 2G Total Coverage	-0.054*	0.004
Income Group 2 * 2G Total Coverage	-0.227*	0.007
Income Group 3 * 2G Total Coverage	-0.427**	0.002
Income Group 4 * 2G Total Coverage	-0.265***	0.006
Household Size * 2G Total Coverage	0.090	0.0007
Age * 2G Total Coverage * GSM	0.046	0.009
Income Group 2 * 2G Total Coverage * GSM	-0.506***	0.006
Income Group 3 * 2G Total Coverage * GSM	0.131	0.001
Income Group 4 * 2G Total Coverage * GSM	-0.209**	0.003
Household Size * 2G Total Coverage * GSM	-0.379*	0.003
Age * 3G Total Coverage	0.045**	0.002
Income Group 2 * 3G Total Coverage	0.473	0.006
Income Group 3 * 3G Total Coverage	0.072**	0.026
Income Group 4 * 3G Total Coverage	-0.595***	0.020
Household Size * 3G Total Coverage	0.371	0.005
Age * 3G Total Coverage * UMTS	0.266	0.007
Income Group 2 * 3G Total Coverage * UMTS	0.511**	0.001
Income Group 3 * 3G Total Coverage * UMTS	-1.126	0.000
Income Group 4 * 3G Total Coverage * UMTS	0.238*	0.001
Household Size * 3G Total Coverage * UMTS	0.354***	0.001
Price * Income Group 2	0.059***	0.000
Price * Income Group 3	0.155***	0.001
Price * Income Group 4	0.154***	0.001
Log likelihood	8,632	
Observations	5,568	

Note: The method of estimation is maximum likelihood. Specification is estimated using 1,072 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 $\sigma^2_{verizon}$ is normalized to 1. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.

Table 12
Counterfactual Market Outcomes (Fixed prices and per-unit investment costs)

	Simulated Counterfactual Outcomes			Difference Across Regimes	
	Competing Standards (I)	Uniform Standard (UMTS)	Uniform Standard (CDMA2000)	(UMTS-I)	(CDMA2000-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 (%)					
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 %

Note: This table presents counterfactual market outcomes with (1) Two competing wireless standards, (2) unified UMTS standard network, and (3) unified CDMA2000 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.