Spillover Effects in Complementary Markets: A Study of the Indian Cell Phone and Wireless Service Markets*

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Abstract

This paper studies indirect network effects on firm entry and product variety in the Indian mobile phone industry during the 4G rollout, focusing on the cell phone and wireless service markets. We highlight that the presence of international firms in the cell phone market accelerates 4G deployment in the wireless market, which in turn influences the product choices of domestic firms. Based on an estimated structural model of consumer demand, carriers' 4G network expansions, and cell phone firms product choices, we conduct counterfactual simulations to assess the impact of protectionist policies amid these spillover effects.

Keywords: indirect network effects, complementarity, foreign competition, 4G technology, wireless service, cell phone

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1 Introduction

Indirect network effects occur when the value of a product in one market depends on the availability, price, and quality of products in another market. Examples include the electric vehicle and charging infrastructure markets, the computer hardware and software markets, and the internet and streaming services markets. In each of these examples, the two markets are complementary, and indirect network effects lead to their interdependence and can have significant economic impacts.

In this paper, we study the indirect network effects on product variety and firm entry. Specifically, we highlight and quantify how the presence of technologically more advanced international firms in an open market contributes to the development of a complementary market by encouraging entry, which in turn affects domestic firms in the open market by increasing their profits from new products. In other words, international firms in one market have a cross-market spillover effect on the other market, as well as a within-market spillover effect on domestic firms in the same market. Importantly, consumers benefit from firm entry and increased product variety as a result of these spillovers.

Our context is the Indian cell phone and wireless service markets during the 4G rollout. In India, many consumers buy a cell phone and a wireless service plan separately. A consumer needs both to enjoy the mobile service. In addition, consumers can only enjoy the advanced features of a 4G cell phone with a 4G service, and the high speed of a 4G service with a 4G cell phone. Therefore, the cell phone and wireless service markets are complementary, and in particular, there is complementarity between 4G phones and 4G services. While the wireless service market is dominated by Indian carriers, the cell phone market has a strong presence of international cell phone firms, including other Asian and non-Asian firms.

The spillovers that we study in this paper operate through the following three-step channel: First, because international cell phone firms have technological advantages over Indian firms and have already produced 4G phones for international markets, they are more likely to sell 4G phones in the Indian cell phone market. In anticipation of this, wireless carriers have higher incentives to start building their 4G networks than in a scenario without these international cell phone firms. We call this a "cross-market spillover effect": the presence of international firms in the cell phone market affects the development in the wireless service market. Second, as the marginal cost of phones declines over time, the cell phone market expands, providing incentives for carriers to continue rolling out their 4G networks. Again, this is a cross-market spillover effect. Third, as 4G network coverage expands, Indian cell phone firms may find it profitable to sell 4G phones themselves. Thus, international cell phone firms have an indirect "within-market spillover effect" on the domestic cell phone firms. As a result of these spillovers, consumers benefit from a faster rollout of 4G networks and a greater variety of 4G phones.

To quantify these spillover and welfare effects, we develop and estimate a structural model of demand, network expansion, product choice, and pricing in the Indian cell phone and wireless service markets. On the demand side, consumers choose a cell phone and a service plan. Cell phones differ in product characteristics, including whether they are 2G, 3G, or 4G phones. Plans differ in terms of carriers and technologies (2G, 3G, or 4G networks). On the supply side, carriers' 4G network rollouts are captured by a dynamic discrete game. Embedded in this dynamic game is a two-stage static game in which, given current 4G networks, cell phone firms decide which phones to sell in the first stage, and both cell phone firms and wireless carriers choose their prices (phone prices and plan prices) in the second stage.

We estimate the model using a newly compiled dataset on both the cell phone and wireless service markets in India. Specifically, we obtain data on the prices, characteristics, and sales of both cell phone and wireless service plans at the national level between 2011 and 2018. We also collect data on each carrier's network at the regional level for each technology and each quarter during the same period. Finally, we supplement the data with information on the population at the regional level and income at the region/year level.

Our estimates yield four results that support spillover effects. First, we find that consumers prefer to use a 4G cell phone with 4G service, even though 4G cell phones are compatible with 2G or 3G networks. This finding suggests that 4G phones and 4G networks are complementary, so that the market structure in the cell phone market affects wireless carriers' 4G network deployment decisions and, conversely, 4G network coverage affects cell phone firms' product and pricing decisions. Second, the markups for international 4G phones are higher than those for Indian 4G phones. This means that international cell phone firms are more likely to introduce 4G phones, making it more profitable for wireless carriers to start building their 4G networks. Third, the marginal cost of producing 4G phones declines over time. The downward trend in marginal cost can lead to lower prices and more 4G phones, making the purchase of a 4G cell phone more attractive to consumers and, in turn, providing further incentives for carriers to expand their 4G networks over time. Fourth, while Indian cell phone firms are less efficient at producing high-quality phones, they face lower costs for producing low-quality phones, suggesting that there is room for Indian cell phone firms to introduce low-end 4G phones later in India's 4G rollout as 4G networks expand.

In summary, the first finding provides the basis for the spillover effects. The second and third findings support the cross-market spillover effect in the initial stage of 4G deployment and in the later stage of continued expansion. The fourth finding gives rise to the within-market spillover effect because it implies that Indian cell phone firms can potentially benefit from the faster 4G network rollout resulting from the presence of international cell phone firms. Taken together, these four findings support within-market spillovers from international firms to domestic Indian firms in the cell phone market and cross-market spillovers to the wireless service market.

Using the estimated model, we conduct two sets of counterfactual simulations. In the first counterfactual simulation, we quantify the impact of a policy to ban low-cost Chinese phones. The Indian government is considering banning low-cost Chinese phones priced below INR 12,000. This initiative aims to eliminate Chinese cell phone firms from the lower end of the Indian cell phone market.

In the second set of counterfactual simulations, we compare two subsidy policies, one offering subsidies to all 4G phones including international phones and the other offering subsidies only to Indian 4G phones. Due to indirect network effects, subsidies in the cell phone market can accelerate 4G network expansions in the wireless service market and, in turn, encourage 4G phone offerings in the cell phone market. While the first policy does not impose any restrictions on subsidies, the second policy is combined with a protectionist restriction. Comparing the outcomes under these two subsidy policies therefore allows us to learn about the effect of protectionism in subsidy design in such a market with indirect network effects.

In each counterfactual simulation, we recompute the equilibrium of the dynamic network expansion game, as well as the equilibrium product choice and prices. We compare the evolution of the number of regions and population covered by 4G networks with that in the data to quantify the cross-market spillover effect. We compare the evolution of the number and sales of Indian 4G phones with that in the data to quantify the within-market spillover effect. We do not yet have counterfactual simulation results. Intuitively, we expect a slower expansion of 4G network coverage under the Chinese low-cost phone ban in the first counterfactual simulation. This is due to the estimated higher markups for international cell phone firms in selling 4G phones and the estimated complementarity between 4G phones and 4G networks. Consequently, we expect later adoption and slower growth of 4G phones in the cell phone market due to slower 4G network rollout. As for the comparison of the two subsidy policies in the second set of counterfactual simulations, we expect 4G deployment to be slower under the protectionism subsidy policy given the positive spillovers from international cell phones to the wireless service market. Moreover, the protectionist subsidy policy may be worse than the unrestricted subsidy policy even when focusing on domestic consumer surplus, domestic firm profits, and subsidy expenditures.

By studying two complementary markets simultaneously, this paper contributes to the literature on indirect network effects between complementary markets. Examples in the literature include Gandal, Kende, and Rob (2000) on the diffusion of CD systems (CD players and CD titles), Lee (2013) on the effect of exclusivity in the game hardware and software markets, Springel (2021) on subsidies in the electric vehicle and charging station markets, and Li (2023) on the effect of compatibility in charging standards also in the electric vehicle and charging station markets. We contribute to this literature with a new topic and a new pair of markets: how the presence of technologically more advanced international firms in the cell phone market helps the development of the complementary wireless service market, and in turn, affects domestic firms in the cell phone market and how consumers benefit from such spillovers.

By studying both the product choices of cell phone firms and the network expansion decisions of carriers, this paper is related to both the endogenous product choice literature and the firm entry literature. Examples include Draganska, Mazzeo, and Seim (2009), Fan (2013), Eizenberg (2014), Wollmann (2018), Chaves (2020), Fan and Yang (2020, 2024), and Kwon (2023) for endogenous product choice, and Collard-Wexler (2013), Dunne, Klimek, Roberts, and Xu (2013), Sweeting (2013), Fan and Xiao (2015), and Mohapatra and Zhang (2024) for dynamic entry games. We embed a static cell phone product choice model into a dynamic network expansion model to study firms' decisions in both markets and, more importantly, the interdependence between them.

By studying the Indian mobile industry, this paper contributes to the literature studying the telecommunication industry. Examples in this literature include Fan and Xiao (2015), Björkegren (2019), Fan and Yang (2020), Callejas, Chatterjee, and Mohapatra (2022), Granja (2024) and Elliott, Houngbonon, Ivaldi, and Scott (2024). While most of these papers focus on either the cell phone market or the provider market, we study both markets and their interdependence. Also, similar to Björkegren (2019) and Granja (2024), this paper studies the telecommunication industry in a developing country, where mobile services play a vital role for economic development and consumer well-being.

Finally, by studying the effect of opening a market to international competitors, this paper is related to the literature on the effect of foreign competition on domestic markets. Papers focusing on the competitive effect find that increased foreign competition increases market efficiency and reduces firms' markups.[1] Papers examining the externalities of foreign direct investment on domestic firms focus mainly on productivity and find mixed results.[2] We add to this literature with a study in which foreign competition in a market can potentially benefit

[1] For example, Levinsohn (1993), Harrison (1994), and Krishna and Mitra (1998). See Tybout (2008) for a survey on this topic.

[2] See Harrison and Rodríguez-Clare (2010) for a survey.

domestic firms in that market by helping the development of a complementary market, and benefit consumers by increasing product availability in both markets.

From a policy perspective, this paper contributes to the debate on whether the Indian cell phone market is in need of protection and whether international cell phone firms are harming domestic cell phone firms. There have been complaints in the media that international cell phone firms, especially Chinese firms, introduced their 4G phones before 4G networks were widespread in India, thereby crowding out domestic cell phone firms. In this paper, we provide evidence against protectionism in this industry. We show that the early entry of 4G phones by international cell phone firms is beneficial for the complementary wireless service market due to the indirect network effect, and in turn increases the profitability of selling a 4G phone in the cell phone market, again due to the indirect network effect. As a result, 4G networks are rolled out faster and more 4G phones are offered. Both of these effects benefit consumers, although the net effect on domestic cell phone firms depends on the comparison of a direct competitive effect, which reduces their profits, and an indirect spillover effect, which increases their profits by affecting the complementary market. This finding – the presence of technologically advanced firms in one market increases product variety and promotes technology diffusion in both markets to the benefit of consumers – is likely to hold for many industries consisting of complementary markets. For developing countries, technologically advanced firms are typically foreign firms. Therefore, their presence in a market requires that the market be opened to international competitors.

The remainder of the paper proceeds as follows. We describe the setting and our data in Section 2 and our model in Section 3. We explain our estimation procedure and present the estimation results in Section 4. The counterfactual simulation results are presented in Section 5. Section 6 concludes.

2 Industry Background and Data

In this section, we describe the industry, summarize the data, and present data patterns for the cell phone and wireless services markets.

2.1 Industry Background

The Indian mobile industry consists of two markets: the cell phone market and the wireless service market. A consumer must purchase a cell phone and a wireless service plan in order to enjoy mobile service. Many consumers in India purchase a cell phone and a plan separately. One exception is Jio, a carrier that sells standalone plans that any cell phone owner can purchase. Between 2015 and 2017, Jio also sold standalone cell phones under the brand name LYF. Since 2017Q3, Jio has been selling phone/plan bundles, where phones (called JioPhones) can only be used on Jio's network.

The wireless services market consists of eight carriers. They are Airtel, Vodafone, Idea, BSNL (Bharat Sanchar Nigam Limited), Reliance Jio, Reliance Communications, Aircel, and MTNL (Mahanagar Telephone Nigam Limited), in descending order of the total number of subscribers during our sample period. These eight carriers operated in different regions of India. The Department of Telecommunications divides India into 22 telecommunications regions. These regions are further divided into four categories (Metro and Categories A, B, C) according to their infrastructure facilities and income levels, with Metro regions being the most developed and Category C regions being the least developed.

The cell phone market consists of both domestic and international cell phone firms. In our sample, there are four Indian firms (Intex, LYF, Lava, and Micromax), five Chinese firms (Gionee, Lenovo, Oppo, Vivo, and Xiaomi), one Korean firm (Samsung), and two non-Asian firms (Apple and Microsoft/Nokia).

2.2 Data

We obtain cell phone data from Counterpoint Research and carrier data from GSMA Intelligence. Our sample period is between 2011 and 2018. We supplement the data with hand-collected information on whether a given carrier operates a 3G or 4G network in a given region and quarter. The 2G network was present in all regions prior to the start of our sample period.

Our cell phone data contain information on sales, prices, and phone characteristics. The data cover all cell phones sold in India between 2011 and 2018. We keep a cell phone firm in our sample if its 3G phone sales are at least 5% of all 3G phone sales and its 4G phone sales are at least 1% of all 4G phone sales. For each cell phone in our data, we observe its firm identity, technology (a 2G, 3G, or 4G phone), screen size, camera resolution, memory, storage, and battery capacity. Sales and price data are available at the annual level between 2011 and 2014 and at the monthly level between 2015 and 2018. We aggregate the data to the quarterly level between 2015 and 2018 to be consistent with the frequency of the carrier data.

Our carrier data also cover the years 2011 to 2018. At the regional level, we observe whether a given carrier offers a particular technology (2G, 3G, or 4G) in each quarter. At the national level, we observe the number of subscribers for each carrier/technology/quarter combination and the average monthly revenue per user for each carrier/quarter combination.

We treat the latter as the monthly price. Although a carrier may offer multiple plans of the same technology, we do not observe sales or prices at such a finer level.[3] For simplicity, we will refer to a carrier/technology combination as a plan from now on.

We consider the population over 15 years of age as potential buyers. According to the 2011 Census, the population aged 15 and older represents 69% of the total population in India. We obtain the annual population in India between 2011 and 2018 from the United Nations Population Division and the share of the population in each region from the 2011 Census. We combine regional share data with annual national population data and multiply their product by 69% to obtain the market size in each region/year combination.

As a proxy for income at the regional level, we obtain the annual data of "Net State Domestic Product" for each region from the Reserve Bank of India (India's central bank). As in many developing countries, income is not well measured or defined in India. Therefore, we use per-capita state domestic product as a proxy for income. We use CPI data to deflate prices and income to the 2015 INR[4]

2.3 Data Patterns

We present summary statistics in Appendix A. In this section, we highlight three data patterns with respect to the cell phone and wireless service markets.

First, international cell phone firms, especially other Asian firms, play an important role in the cell phone market. For each cell phone firm, we compute its total sales of 3G and 4G phones in the sample, and then report the ratio of that firm's total sales to the sum of all firms' sales in Table 1. From the table, we can see that Indian cell phone firms, other Asian firms, and non-Asian firms account for 28%, 64%, and 8% of sales, respectively, indicating that international firms are strong competitors in the market.

Second, while Indian cell phone firms do well in the lower end of the market, international firms dominate the higher end. Table 2 shows the sales shares of cell phone firms by origin and by price range for 4G cell phones. Specifically, we consider three price ranges defined by terciles. The table shows that while Indian cell phone firms account for 59% of total 4G phone sales in the low-price range, their share drops dramatically to 5% and 1% in the medium and high price ranges. The opposite is true for other Asian firms: Their total share increases from 41% in the low-price range to 95% and 89% in the two higher price ranges.

[3]While it is not ideal to ignore within-carrier/technology-across-plan variation due to data limitations, we note that the average monthly price of a plan is as low as 121 INR, which is about 1/100 of the average cell phone price.

[4]CPI data are obtained from the Federal Reserve Economic Data (https://fred.stlouisfed.org/series/INDCPIALLAINMEI).

Table 1: Cell Phone Firms and Sales Shares

Origin	Firm	Sales Share	Total
Indian	Intex	3.3%	
Indian	Jio	15.7%	
Indian	Lava	3.2%	
Indian	Micromax	6.0%	28%
Other-Asian	Gionee	1.3%	
Other-Asian	Lenovo	4.9%	
Other-Asian	Oppo	4.8%	
Other-Asian	Samsung	33.0%	
Other-Asian	Vivo	6.2%	
Other-Asian	Xiaomi	13.7%	64%
Non-Asian	Apple	1.7%	
Non-Asian	Microsoft/Nokia	6.1%	8%

Notes: This table lists the cell phone firms in our sample. Sales share is the ratio of "total 3G and 4G phone units sold by a firm in our sample" to "total 3G and 4G cell phone units sold in our sample."

Non-Asian firms are present only in the high price range, with a total share of 10% in this market segment.

Table 2: 4G Cell Phone Sales Share by Country Origin and Price Range

Origin	Low-Price	Medium-Price	High-Price
Indian	59%	5%	1%
Other Asian	41%	95%	89%
Non-Asian	-	-	10%

Notes: This table shows the sales shares of 4G phones by phone firm origin and price range. The price ranges are defined by the terciles of cell phone prices. The sales share is the ratio of "total 4G phone units sold by all firms of a given origin and in a given price range" to "total 4G phone units sold in a given price range."

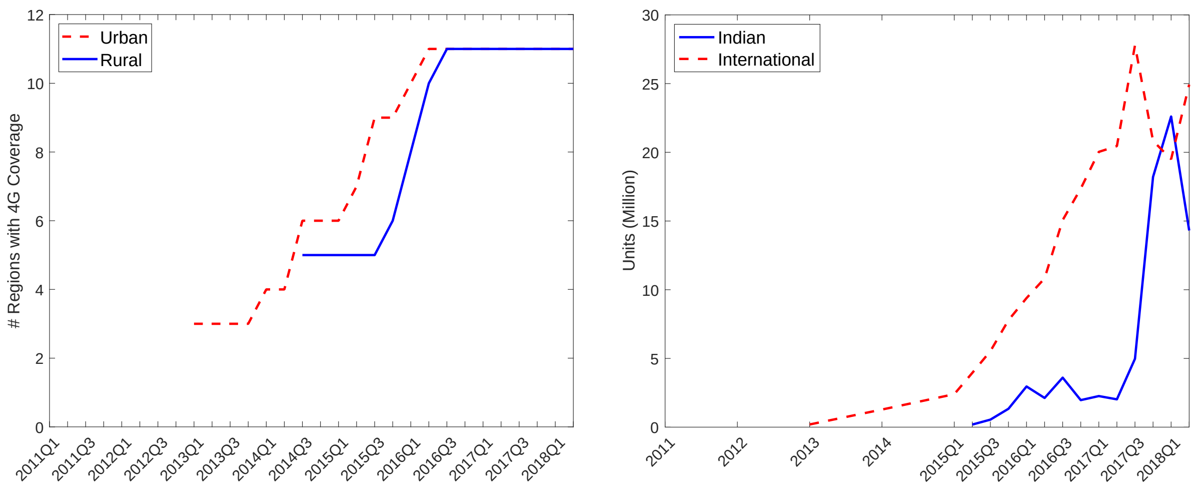
Third, there have been comovements in the markets for phones and wireless services. Panel (a) of Figure 1 presents the number of urban and rural regions covered by 4G networks over time. This panel shows that 4G network coverage in India started in 2013,[5] gradually

[5]In 2012Q2 and 2012Q4, Airtel launched its 4G network in two cities, Kolkata and Pune, respectively, but only on an experimental basis.

expanded among urban regions followed by rural regions, and finally reached all 22 regions in 2016Q3. Panel (b) shows 4G phone sales by country of origin over time. We can see that with the expansion of the 4G network, the sales of 4G phones increased over time. International cell phone firms started selling 4G phones in 2013. Indian cell phone firms entered the 4G market later. Their sales started at a low level initially and skyrocketed in 2017.

Figure 1: 4G Network Coverage and 4G Cell Phone Sales Over Time

(a) # Regions Covered by 4G Networks (b) Sales of 4G Phones



Notes: The left panel plots the number of urban and rural regions with 4G coverage over time. The right panel plots the units sold (in millions) of 4G phones over time by Indian, other Asian, and non-Asian cell phone firms. In the left panel, we have quarterly data. In the right panel, we have annual data between 2011 and 2014 and quarterly data between 2015Q1 and 2018Q2.

In summary, our data shows that international firms play a large role in the cell phone market. They started selling 4G phones first. The growth of 4G phone sales and the rollout of 4G networks coincided. Indian cell phone firms introduced 4G phones later, after 4G coverage expanded.

3 Model

To quantify how the presence of technologically more advanced international firms in the cell phone market affects the development of the wireless service market (the cross-market spillover effect), domestic firms in the cell phone market (the within-market spillover effect), and consumers (the welfare effect), we develop and estimate a structural model of demand, network expansion, product choice, and pricing in the Indian cell phone and wireless service markets.

3.1 Demand

Demand is described by a discrete-choice model. Consumers choose a cell phone and a wireless plan, or the outside option of not using the mobile service. A consumer needs both a phone (indexed by j) and a plan (indexed by k) to enjoy mobile service. Let $\mathcal{J}_t$ be the set of phones at time t and $\mathcal{K}_{rt}$ be the set of plans in region r at time t. Let $\mathcal{B}(\mathcal{J}_t, \mathcal{K}_{rt})$ be the set of phone/plan combinations available to consumers in region r at time t. It includes all combinations (j, k) such that $j \in \mathcal{J}_t$ and $k \in \mathcal{K}_{rt}$, except that 3G phones are not compatible with 4G plans, 2G phones are not compatible with 3G or 4G plans, and JioPhones are not compatible with non-Jio plans.

Consumer i gets the following indirect utility from buying phone j and plan k at time t:

$$u_{ijkt} = x_{jkt}\beta - \alpha_{it}(p_{jt} + p_{kt}) + \xi_{jt}^{(ph)} + \xi_{kt}^{(pl)} + \varepsilon_{ijkt}, \tag{1}$$

where the vector x_{jkt} is a vector of observable phone and plan characteristics, p_{jt} is the price of phone j, and p_{kt} is the price of plan k.[6] We allow for heterogeneity in consumer price sensitivity: $\alpha_{it} = \alpha_0 + \alpha_1 Inc_r + \sigma_\alpha v_{it}$, where Inc_r is the logarithm of the average income in region r in 1000 INR and v_{it} is i.i.d. and follows a standard normal distribution. We also include the terms $\xi_{jt}^{(ph)}$ and $\xi_{kt}^{(pl)}$ to capture the unobservable characteristics of the phone and the plan, where the superscripts (ph) and (pl) stand for "phone" and "plan", respectively. Finally, the term ε_{ijkt} captures the consumer's idiosyncratic taste and is assumed to be i.i.d. and follows a type-1 extreme value distribution. The utility of the outside option is normalized to $u_{i0t} = \varepsilon_{i0t}$.

The vector x_{jkt} includes three sets of covariates. First, it includes a quality index of phone j, which depends on the observable product characteristics x_j as $q_j = x_j\rho$, where ρ are the parameters to be estimated and the first dimension of ρ is normalized to 1. In other words, following Fan and Yang (2020), who also study the cell phone market, we assume that consumer utility depends on phone characteristics only through the quality index. This parsimonious functional form allows us to characterize a phone by its quality index and later define potential products based on their quality indices. Second, x_{jkt} includes phone technology fixed effects, plan technology fixed effects, and a dummy variable $\mathbb{1}(4G_j, 4G_k)$ that takes the value 1 if and only if phone j is a 4G phone and plan k is a 4G plan. By including the variable $\mathbb{1}(4G_j, 4G_k)$, we allow consumers to derive a differential utility from using a 4G phone on a 4G network over and above the advantages of a 4G phone captured

[6] The price of a plan is the monthly price of a plan multiplied by the average length of time that a consumer owns a phone before replacing it. We use 20.07 months as the average duration before 2018 and 16.43 months after 2018 (Zeebiz, 2017).

by phone characteristics (including the 4G phone dummy). Third, in addition to phone technology and plan technology fixed effects, we also include cell phone firm fixed effects, carrier fixed effects, and time fixed effects to capture systematic differences at different levels.

The market share of combination jk in region r at time t is

$$\begin{aligned} & s_{jkrt}(\boldsymbol{p}_{rt}, \boldsymbol{x}_{rt}, \boldsymbol{\xi}_{rt}; \mathcal{B}(\mathcal{J}_t, \mathcal{K}_{rt})) \\ = & \int \frac{exp(x_{jkt}\beta - \alpha_{it}(p_{jt} + p_{kt}) + \xi_{jt}^{(ph)} + \xi_{kt}^{(pl)})}{1 + \sum_{j'k' \in \mathcal{B}(\mathcal{J}_t, \mathcal{K}_{rt})} exp(x_{j'k't}\beta - \alpha_{it}(p_{j't} + p_{k't}) + \xi_{j't}^{(ph)} + \xi_{k't}^{(pl)})} dG_r(\alpha_{it}), \end{aligned} \tag{2}$$

where $\boldsymbol{p}_{rt} = (p_j + p_k, jk \in \mathcal{B}(\mathcal{J}_t, \mathcal{K}_{rt}))$, $\boldsymbol{x}_{rt} = (x_{jkt}, jk \in \mathcal{B}(\mathcal{J}_t, \mathcal{K}_{rt}))$, and $\boldsymbol{\xi}_{rt} = ((\xi_{jt}^{(ph)}, j \in \mathcal{J}_t), (\xi_{kt}^{(pl)}, k \in \mathcal{K}_{rt}))$. Finally, $G_r(\alpha_{it})$ is the distribution function of α_{it} in region r.

To match our national-level market share data, for each phone j, we sum the market share in (2) first over all its compatible plans in a region and then over regions $r = 1, ..., R$. Similarly, the market share of plan k is the aggregation over all regions and all phones compatible with that plan. Specifically, let w_r be the population weight of region r in the nation. The market shares of phone j and plan k at time t are, respectively,

$$s_{jt}^{(ph)}(\boldsymbol{p}_t, \boldsymbol{x}_t, \boldsymbol{\xi}_t; \mathcal{J}_t, \mathcal{K}_t) = \sum_{r=1}^{R} w_r \cdot \sum_{k:(j,k) \in \mathcal{B}(\mathcal{J}_t, \mathcal{K}_{rt})} s_{jkrt}(\boldsymbol{p}_{rt}, \boldsymbol{x}_{rt}, \boldsymbol{\xi}_{rt}; \mathcal{B}(\mathcal{J}_t, \mathcal{K}_{rt})), \tag{3}$$

$$s_{kt}^{(pl)}(\boldsymbol{p}_t, \boldsymbol{x}_t, \boldsymbol{\xi}_t; \mathcal{J}_t, \mathcal{K}_t) = \sum_{r=1}^{R} w_r \cdot \sum_{j:(j,k) \in \mathcal{B}(\mathcal{J}_t, \mathcal{K}_{rt})} s_{jkrt}(\boldsymbol{p}_{rt}, \boldsymbol{x}_{rt}, \boldsymbol{\xi}_{rt}; \mathcal{B}(\mathcal{J}_t, \mathcal{K}_{rt})), \tag{4}$$

where $\mathcal{K}_t = \{\mathcal{K}_{rt}\}_{r=1}^{R}$ and $(\boldsymbol{p}_t, \boldsymbol{x}_t, \boldsymbol{\xi}_t)$ are defined similarly to $(\boldsymbol{p}_{rt}, \boldsymbol{x}_{rt}, \boldsymbol{\xi}_{rt})$ for all phones and plans in the nation. In equations (3) and (4), a time period is a quarter. For the sample period when we have only yearly data instead of quarterly data for phone sales, we aggregate the phone market share in (3) across quarters within a year.[7]

3.2 Supply

On the supply side, carriers choose their 4G networks. In each period, among the regions where a carrier has not established its 4G network, the carrier chooses a subset of these regions to expand its 4G network. An empty subset indicates no expansion in that period. Since establishing a 4G network in a region is an absorbing state, this network expansion decision is dynamic. In such a dynamic game, each carrier's period profit is determined by a static game in which cell phone firms choose the set of phones to sell given the network

[7]In this case, the unobservable demand shock ξ_{jt} is at the phone/year level instead of the phone/quarter level.

structure in the country. Intuitively, the greater the 4G network coverage, the greater the profits that cell phone firms get from selling 4G phones. Conversely, the more 4G phones expected to be sold in a region, the more profitable it is for a carrier to expand its 4G network into that region. Our model allows for this interdependence between the cell phone and wireless service markets. In our model, cell phone firms and carriers also decide the prices of phones and plans.

We model the product choice of cell phone firms as a static problem. We make this static assumption for three reasons. First, it would be computationally prohibitive to solve a dynamic game with two sets of interdependent firms, each making a discrete decision with a large choice set (carriers choose a subset of regions in which to deploy their 4G networks, and cell phone firms choose a subset of their potential products to sell). Second, this static assumption is somewhat justified because the phones in the Indian market are either already designed for the global market or are below the technology frontier during our sample period. As a result, selling these phones is unlikely to involve large sunk costs of innovation. Third, although this part of the model is assumed to be static, its combination with our dynamic model of network expansion allows us to capture the spillover effects at the center of the paper: the presence of international firms in the cell phone market makes it more likely that 4G phones are sold. In anticipation of this, carriers have higher incentives to roll out their 4G networks compared to a scenario without international cell phone firms. Over time, any changes in the cell phone market that lead to an increase in 4G cell phone sales (e.g., lower marginal costs over time) give carriers incentives to expand their 4G network. Eventually, with greater 4G network coverage, even Indian cell phone firms may find it profitable to sell 4G phones.

In what follows, we first describe the static game of product choice and prices, and then explain the dynamic discrete game of 4G network expansion.

3.2.1 Static Game of Product Choice and Prices

The static game consists of two stages. In the first stage, cell phone firms choose products given the networks. In the second stage, both cell phone firms and carriers choose prices given the networks and phones. We describe these two stages in reverse order.

Pricing Stage At the pricing stage, cell phone firms and carriers observe the set of available phones and plans, as well as the demand and marginal cost shocks for each phone and plan. The cell phone firm f chooses the prices of its phones (denoted by $\mathcal{J}_{ft}$) to maximize its profit:

$$\max_{\{p_{jt}:j\in\mathcal{J}_{ft}\}} \sum_{j\in\mathcal{J}_{ft}} s_{jt}^{(ph)}(\boldsymbol{p}_t, \boldsymbol{x}_t, \boldsymbol{\xi}_t; \mathcal{J}_t, \mathcal{K}_t)(p_{jt} - c_{jt}^{(ph)}), \tag{5}$$

where $c_{jt}^{(ph)}$ is the marginal cost for phone j at time t. We parameterize it as

$$\begin{aligned} log(c_{jt}^{(ph)}) = \gamma_0 + \gamma_1 \mathbb{1}(Indian)_j + (\tau_0 + \tau_1 \mathbb{1}(Indian)_j)\, q_j \\ + \eta_1 t \mathbb{1}(Indian)_j + \eta_2 t \mathbb{1}(Int'l) + \omega_{jt}^{(ph)}. \end{aligned} \tag{6}$$

In this specification, the marginal cost depends on the quality of a phone. We allow both the level of the marginal cost and its slope with respect to quality to differ between international and Indian cell phone firms. We also include an origin-specific time trend. Finally, $\omega_{jt}^{(ph)}$ is the marginal cost shock.

Similarly, carrier c chooses the prices of its plans (denoted by $\mathcal{K}_{ct}$) to maximize its profit:

$$\max_{\{p_{kt}:k\in\mathcal{K}_{ct}\}} \sum_{k:k\in\mathcal{K}_{ct}} s_{kt}^{(pl)}(\boldsymbol{p}_t, \boldsymbol{x}_t, \boldsymbol{\xi}_t; \mathcal{J}_t, \mathcal{K}_t)(p_{kt} - c_{kt}^{(pl)}), \tag{7}$$

where $c_{kt}^{(pl)}$ is the marginal cost for plan k at time t, decomposed into a plan fixed effect and a shock: $c_{kt}^{(pl)} = Plan_k + \omega_{kt}^{(pl)}$.

An exception to the profit-maximization problems in (5) and (7) is the problem of Jio. Between 2016Q3 and 2017Q1, Jio sold both a network plan (i.e., Jio 4G plan) and a set of 4G phones under the brand name LYF. Therefore, Jio's problem is to choose both the price of its plan (p_{kt}) and the prices of LYF phones ($\{p_{jt} : j \in \text{LYF}_t\}$) to maximize the total profit from both phone sales and plan sales. From 2017Q2, while continuing to sell its network plan, Jio stopped selling LYF phones and instead sold phone/plan bundles where the phones (called JioPhones) can only be used on Jio's network. In this case, Jio's problem is to choose both the price of its plan (p_{kt}) and the prices of the bundles ($\{p_j : j \in \text{Jiophone}_t\}$) to maximize the total profit from selling the standalone plan and the bundles. In sum, Jio's profit-maximization problem is

$$\begin{aligned} \max_{\{p_{jt}:j\in\mathcal{J}_{ft}\}, p_{kt}} \quad & \sum_{j:j\in\mathcal{J}_{ft}} s_{jt}^{(ph)}(\boldsymbol{p}_t, \boldsymbol{x}_t, \boldsymbol{\xi}_t; \mathcal{J}_t, \mathcal{K}_t)(p_{jt} - c_{jt}^{(ph)}) \\ & + s_{kt}^{(pl)}(\boldsymbol{p}_t, \boldsymbol{x}_t, \boldsymbol{\xi}_t; \mathcal{J}_t, \mathcal{K}_t)(p_{kt} - c_{kt}^{(pl)}), \end{aligned} \tag{8}$$

where $\mathcal{J}_{ft}$ represents either the LYF phones or the JioPhones and $c_{jt}^{(ph)}$ represents either the marginal cost of a LYF phone or that of a JioPhone bundle.

Let $p_{jt}^*(\mathcal{J}_t, \mathcal{K}_t, \boldsymbol{\xi}_t, \boldsymbol{\omega}_t)$ and $p_{kt}^*(\mathcal{J}_t, \mathcal{K}_t, \boldsymbol{\xi}_t, \boldsymbol{\omega}_t)$ be the equilibrium prices for phone j and plan k, where $\boldsymbol{\omega}_t$ is the collection of marginal cost shocks. We suppress the variable $\boldsymbol{x}_t$ here because it is determined by $\mathcal{J}_t$. Correspondingly, we denote the equilibrium profit for a cell phone firm f and a carrier c as

$$\pi_{ft}^{(phone)}(\mathcal{J}_t, \mathcal{K}_t, \boldsymbol{\xi}_t, \boldsymbol{\omega}_t) \text{ and } \pi_{ct}^{(carrier)}(\mathcal{J}_t, \mathcal{K}_t, \boldsymbol{\xi}_t, \boldsymbol{\omega}_t). \tag{9}$$

Since demand and marginal cost shocks are realized in the second stage, we also define the expected variable profits, which we will use to describe the first stage below. Specifically, the expected variable profits are

$$\begin{aligned} \tilde{\pi}_{ft}^{(phone)}(\mathcal{J}_t, \mathcal{K}_t) &= E_{(\boldsymbol{\xi}_t, \boldsymbol{\omega}_t)}\left[\pi_{ft}^{(phone)}(\mathcal{J}_t, \mathcal{K}_t, \boldsymbol{\xi}_t, \boldsymbol{\omega}_t)\right] \\ \tilde{\pi}_{ct}^{(carrier)}(\mathcal{J}_t, \mathcal{K}_t) &= E_{(\boldsymbol{\xi}_t, \boldsymbol{\omega}_t)}\left[\pi_{ct}^{(carrier)}(\mathcal{J}_t, \mathcal{K}_t, \boldsymbol{\xi}_t, \boldsymbol{\omega}_t)\right]. \end{aligned} \tag{10}$$

Product Choice Stage At the product choice stage, cell phone firms observe each carrier's network and thus the set of plans available in each region $\mathcal{K}_{rt}$. Each cell phone firm f is endowed with a set of potential phones $\mathcal{H}_{ft}$ and decides on the set of phones to offer, i.e., $\mathcal{J}_{ft} \subseteq \mathcal{H}_{ft}$, in order to maximize its expected profit, which is the difference between the expected variable profit and the fixed costs associated with offering the set $\mathcal{J}_{ft}$.

Formally, the profit-maximization problem of cell phone firm f at the product choice stage is

$$\max_{\mathcal{J}_{ft} \subseteq \mathcal{H}_{ft}} \tilde{\pi}_{ft}^{(phone)}(\mathcal{J}_{ft}, \mathcal{J}_{-ft}, \mathcal{K}_t) - \sum_{j \in \mathcal{J}_{ft}} C_{jt}, \tag{11}$$

where C_{jt} is the fixed cost of offering phone j. Here, we rewrite $\tilde{\pi}_{ft}^{(phone)}(\mathcal{J}_t, \mathcal{K}_t)$ in (10) as $\tilde{\pi}_{ft}^{(phone)}(\mathcal{J}_{ft}, \mathcal{J}_{-ft}, \mathcal{K}_t)$ to separate what firm f can choose (its own product portfolio $\mathcal{J}_{ft}$) from its opponents' portfolios ($\mathcal{J}_{-ft}$).

The equilibrium of this stage is each firm's phone portfolio given the carriers' networks. Let $\mathcal{J}_t^*(\mathcal{K}_t) = (\mathcal{J}_t^*(\mathcal{K}_t), f = 1, ..., F)$ represent the equilibrium product portfolios for the F cell phone firms on the market.

At this equilibrium, a carrier's expected profit is

$$\Pi_{ct}(\mathcal{K}_t) = \tilde{\pi}_{ct}^{(carrier)}(\mathcal{J}_t^*(\mathcal{K}_t), \mathcal{K}_t), \tag{12}$$

where we plug the product choice equilibrium $\mathcal{J}_t^*(\mathcal{K}_t)$ into carrier c's expected profit in (10). This profit function $\Pi_{ct}(\mathcal{K}_t)$ is the period profit in the dynamic game in the next section.

3.2.2 Dynamic Game of 4G Network Expansion

During the sample period between 2011 and 2018, 4G technology was the new technology and 4G networks were expanding in India. Accordingly, we examine carriers' decisions to expand 4G networks and treat 2G and 3G networks as exogenous in our model.

We focus on the four largest carriers and treat the networks of the other four fringe carriers as exogenous. These four carriers are Airtel, Vodafone, Idea, and Jio, ranked by their total number of subscribers during our sample period. They account for 95% of 4G services.[8]

We model carriers' 4G network expansion decisions as a finite-period dynamic discrete game. The finite-period assumption is consistent with the observation that, by the end of our sample, all four carriers had entered almost all of the regions studied in the paper, and expanding one's 4G network into a region is an absorbing state.[9]

We first introduce some notation to describe the model. Let $\mathcal{R}$ denote the full set of regions and $\mathcal{R}_{ct}$ be the set of regions that carrier c has entered with 4G services. Let the period profit for carrier c at time t be $\Pi_{ct}(\mathcal{R}_t)$ where $\mathcal{R}_t = (\mathcal{R}_{1t}, ..., \mathcal{R}_{4t})$. Note that a carrier's period profit is expressed as a function of the set of plans in each region in equation (12): $\Pi_{ct}(\mathcal{K}_t)$ where $\mathcal{K}_t = \{\mathcal{K}_{rt}\}_{r=1}^{R}$. We can equivalently write it as a function of each carrier's 4G network, i.e., $\Pi_{ct}(\mathcal{R}_t)$ where $\mathcal{R}_t = (\mathcal{R}_{1t}, ..., \mathcal{R}_{4t})$, because whether carrier c offers 4G services in region r (i.e., $r \in \mathcal{R}_{ct}$) uniquely determines whether the "carrier-c/4G" plan is in region r (i.e., "carrier-c/4G" $\in \mathcal{K}_{rt}$) and the 2G and 3G networks are treated as exogenous.

We now describe the model environment, the timing, the Bellman equation, and the equilibrium.

Environment In each period, a carrier's action a_{ct} is to select a subset from the set of regions that it has not entered with 4G services (denoted by $\mathcal{R} \backslash \mathcal{R}_{ct}$). $a_{ct} = \emptyset$ means that this carrier is not expanding in this time period. A non-empty a_{ct} represents the set of new regions that carrier c enters with 4G services this period. For Jio, however, we assume, consistent with the observed data, that its decision is either to enter all regions at once or not at all. In other words, the set of possible actions is $\mathcal{A}_c(\mathcal{R}_{ct}) = \{a : a \subseteq \mathcal{R} \backslash \mathcal{R}_{ct}\}$ for non-Jio carriers and $\mathcal{A}_c(\mathcal{R}_{ct}) = \{\emptyset, \mathcal{R}\}$ for Jio. The entry cost for carrier c to expand its 4G network into regions in a_{ct} is $f_c(a_{ct}, \theta)$. There is also an action-specific shock $\varepsilon_{ct}(a_{ct})$, which

[8] The other four carriers either offered only 2G and 3G services or had very limited 4G services. Specifically, BSNL and MTNL offered only 2G and 3G services during our sample period and did not have the rights to offer 4G networks in any region. Aircel and Reliance Communication operated mostly 2G and 3G networks and offered limited 4G services before exiting the market in 2018.

[9] As explained in the next section, we focus on 12 regions. By the end of our sample, Airtel and Jio had entered all 12 regions, while Idea and Vodafone had entered 11 of them.

is private information.

Timing At the beginning of each period, all carriers observe the network structure $\mathcal{R}_t = (\mathcal{R}_{1t}, ..., \mathcal{R}_{4t})$. Each carrier also observes its own shocks $\varepsilon_{ct} = (\varepsilon_{ct}(a_{ct}), a_{ct} \in \mathcal{A}_c(\mathcal{R}_{ct}))$. Carriers simultaneously decide their actions a_{ct}. In the next period, the network structure becomes $\mathcal{R}_{t+1}$ where $\mathcal{R}_{ct+1} = \mathcal{R}_{ct} \cup a_{ct}$.

Bellman Equation and Equilibrium Let $V_{ct}(\mathcal{R}_t, \varepsilon_{ct})$ be the value function of carrier c at time t and μ be the discount factor. The Bellman equation is

$$\begin{aligned} V_{ct}(\mathcal{R}_t, \varepsilon_{ct}) = \max_{a_{ct} \in \mathcal{A}_c(\mathcal{R}_{ct})} \{ & \Pi_{ct}(\mathcal{R}_t) - f_c(a_{ct}, \theta) + \varepsilon_{ct}(a_{ct}) \\ & + \mu E_{\mathcal{R}_{t+1}} E_{\varepsilon_{ct+1}} (V_{ct+1}(\mathcal{R}_{t+1}, \varepsilon_{ct+1}) | \mathcal{R}_t, a_{ct}) \}. \end{aligned} \tag{13}$$

With a slight abuse of notation, we use $V_{ct}(\mathcal{R}_t)$ to denote the expected value function $E_{\varepsilon_{ct}} V_{ct}(\mathcal{R}_t, \varepsilon_{ct})$. Following the literature, we assume that $\varepsilon_{ct}(a_{ct})$ is i.i.d. and follows a type-1 extreme value distribution with location parameter 0 and scale parameter ϕ. Under this assumption, the Bellman equation becomes

$$\begin{aligned} V_{ct}(\mathcal{R}_t) = \gamma + \phi \ln \Bigg(\sum_{a_{ct} \in \mathcal{A}_c(\mathcal{R}_{ct})} exp \Big(\Big[& \Pi_{ct}(\mathcal{R}_t) - f_c(a_{ct}, \theta) \\ & + \mu E_{\mathcal{R}_{t+1}} (V_{ct+1}(\mathcal{R}_{t+1}) | \mathcal{R}_t, a_{ct}) \Big] / \phi \Big) \Bigg), \end{aligned} \tag{14}$$

where γ is the Euler constant. At $t = T$, the value function $V_{cT}(\mathcal{R}_T)$ depends on the expectation of $V_{cT+1}(\mathcal{R}_{T+1})$ conditional on $(\mathcal{R}_t, a_{ct})$. We define the value function at period $T + 1$ as

$$V_{cT+1}(\mathcal{R}_{T+1}) = \frac{\Pi_{cT}(\mathcal{R}_{T+1})}{1 - \mu}. \tag{15}$$

The equilibrium is a vector of probabilities $\{\Pr_{ct}(a_{ct} | \mathcal{R}_t),\ a_{ct} \in \mathcal{A}_c(\mathcal{R}_{ct})\}$ such that

$$Pr_{ct}(a_{ct} | \mathcal{R}_t) = \frac{exp([\Pi_{ct}(\mathcal{R}_t) - f_c(a_{ct}, \theta) + \mu E_{\mathcal{R}_{t+1}} (V_{ct+1}(\mathcal{R}_{t+1}) | \mathcal{R}_t, a_{ct})] / \phi)}{\sum_{a \in \mathcal{A}_c(\mathcal{R}_{ct})} exp([\Pi_{ct}(\mathcal{R}_t) - f_c(a, \theta) + \mu E_{\mathcal{R}_{t+1}} (V_{ct+1}(\mathcal{R}_{t+1}) | \mathcal{R}_t, a)] / \phi)}, \tag{16}$$

where $V_{ct}(\mathcal{R}_t)$ is the solution to (14) where the expectation in (14) is taken according to the probability in (16).

4 Estimation and Results

In this section, we explain our estimation procedure and present the estimation results. We provide more details on estimation in Appendix B.

4.1 Demand and Marginal Costs

The identification and estimation of the demand and marginal cost parameters are similar to those in Berry, Levinsohn, and Pakes (1995). We estimate these parameters using the Generalized Method of Moments. Demand-side moments are constructed by interacting the unobservable demand shocks $\xi_{jt}^{(ph)}$ and $\xi_{kt}^{(pl)}$ with instrumental variables. We consider two groups of instruments: instrumental variables according to Berry, Levinsohn, and Pakes (1995) and the differentiation instrumental variables according to Gandhi and Houde (2019). The validity of our estimation strategy relies on the timing assumption that firms do not know demand shocks when choosing products. Such a timing assumption is made, for example, in Eizenberg (2014), Wollmann (2018), and Fan and Yang (2020, 2024). In our demand model, we include a rich set of fixed effects to control for systematic variation across phone technologies, plan technologies, cell phone firms, carriers, and time. Thus, although imperfect, it seems reasonable to assume that firm-specific time-varying transitory shocks are unknown to firms when they make their product choices. In the utility function, we are particularly interested in the coefficient of the dummy variable $\mathbb{1}(4G_j, 4G_k)$, which captures whether consumers get an additional utility combining a 4G phone with a 4G network. This coefficient is identified by how phone sales vary with variations in plan choices and by how plan sales vary with variations in phone choices. The supply-side moments are constructed by interacting marginal cost shocks with marginal cost covariates. To construct these moments, we back out marginal costs based on first-order conditions.

Table 3 shows the results of the demand estimation. The estimates indicate that consumers do not like to pay a high price and that price sensitivity decreases with income. With an average income of 122,117 INR, the average price coefficient is -10.91 ($= -36.66 + 5.36 \times \log(122.117)$). We also find that consumers prefer phones with larger screens, higher camera resolution, more storage, and more RAM. For example, increasing the storage from 16GB to 32GB is equivalent to a price decrease of 1,423 INR on average ($= 0.97 \times 1.6/10.91 \times 10K$), which is about 13% of the average price of a 4G phone.

Consumers also gain more utility from using a 4G phone on a 4G network. The estimated coefficient of $\mathbb{1}(\text{4G Phone}) \times \mathbb{1}(\text{4G Network})$ is 4.72, equivalent to a willingness to pay of 4,326 INR given the average price coefficient ($= 4.72/10.91 \times 10K$). It is unsurprising that consumers prefer using a 4G phone on a 4G network (even though 4G phones are

Table 3: Estimation Results: Demand

	Est.	Std. Error
Price (10K INR)	-36.66***	8.82
Price × Income	5.36***	1.50
Screen Size (Inch)	0.69***	0.17
Camera (MP)	0.09***	0.04
Storage (10GB)	0.97***	0.22
RAM (GB)	0.69***	0.25
Battery Capacity (Ah)	0.29	0.19
Plan Price Multiplier	56.65***	4.35
$\mathbb{1}$(4G Phone)× $\mathbb{1}$(4G Network)	4.72***	1.26
Phone Technology FE	Yes	
Plan Technology FE	Yes	
cell phone firm FE	Yes	
Carrier FE	Yes	
Time FE	Yes	
Jio First Year FE	Yes	

Notes: This table reports the estimated demand parameters and their standard errors. For the phone characteristics in the quality index, we report $\beta_q \rho_l$ where β_q is the quality coefficient in the utility function and ρ_l is the weight of the l^{th} characteristic in the quality index $q_j = x_j \rho$. *** $p < 0.01$, * $p < 0.1$.

compatible with 2G and 3G networks) because consumers only enjoy the advanced features of a 4G phone with a 4G network and the high speed of a 4G network with a 4G phone. Such complementarity between 4G phones and 4G networks leads to the interdependence between the behavior of cell phone firms and the decisions of carriers, which is the basis for the spillover effects we study.

Table 4 reports the estimated marginal cost parameters for cell phones. We find that marginal costs increase with quality ($\hat{\tau}_0 > 0$), Indian firms have a cost advantage in producing low-quality phones ($\hat{\gamma}_1 < 0$), but their marginal costs rise faster with quality ($\hat{\tau}_1 > 0$). The finding that Indian firms have a cost advantage in the low-end segment of the cell phone market supports the within-market spillover effect because it implies that there is room for Indian cell phone firms to introduce (low-end) 4G phones when 4G network coverage becomes large enough.

We also find a downward trend in marginal costs for cell phones. The estimated coefficients of the time trend for Indian and international phones both have negative signs and

Table 4: Estimation Results: Phone Marginal Cost

	Est.	Std. Error
Constant (γ_0)	-0.45***	0.12
Quality (τ_0)	0.14***	0.01
$\mathbb{1}$(Indian) (γ_1)	-1.80***	0.27
Quality$\times\mathbb{1}$(Indian) (τ_1)	0.18***	0.05
Time Trend $\times\mathbb{1}$(Indian)	-0.06***	0.01
Time Trend $\times\mathbb{1}$(International)	-0.07***	0.01
Jio Dummy	-0.06	0.05

*** $p < 0.01$, ** $p < 0.05$.

Table 5: Estimated 4G Phone Markups (INR)

Quantile	25%	50%	75%
Indian 4G phones	1,023	1,055	1,106
International 4G phones	1,143	1,271	1,758

are statistically significant. This downward trend in marginal costs supports the continued expansion of the 4G network because decreasing marginal costs can lead to lower prices and greater variety, thus expanding the cell phone market. An expansion in the cell phone market gives carriers in the complementary wireless service market greater incentives to deploy their 4G networks.

Turning to markups, we find that markups for international 4G phones are higher than those for domestic Indian 4G phones. Table 5 shows the quantiles of markups for Indian 4G phones and international 4G phones separately. From the table, we can see that the median markup for an Indian 4G phone is 1,055 INR and for an international 4G phone is 1,271 INR. Both the 25% and 75% quantiles are also higher for an international 4G phone than for an Indian 4G phone. The finding of higher markups for international 4G phones implies that international cell phone firms are more likely to sell 4G phones even with a small 4G network, providing incentives for carriers to start rolling out their 4G networks.

In summary, the estimated complementarity between 4G phones and 4G plans provides the basis for the spillover effects. The estimated higher markups for international 4G phones support the cross-market spillover effect in the initial stage of 4G deployment. The finding of decreased marginal costs over time supports the cross-market spillover effect in the later stage of continued 4G network expansion. Finally, the finding that Indian firms have a cost advantage in the lower-end market segment gives rise to within-market spillover effects because it implies Indian cell phone firms could potentially gain from the accelerated 4G network deployment spurred by their international counterparts. Collectively, these empirical results support within-market spillovers from international firms to Indian firms in the cell phone market, as well as cross-market spillovers affecting the wireless service market.

4.2 Phone Fixed Costs

We estimate the fixed cost of a phone C_{jt} by exploiting the non-profitable deviation condition of Nash equilibrium of the product choice game. Specifically, Nash equilibrium implies that both dropping a product and adding a product do not increase the profit. In other words, for any phone $j \in \mathcal{J}_{ft}$,

$$\tilde{\pi}_{ft}^{(phone)}(\mathcal{J}_{ft}, \mathcal{J}_{-ft}, \mathcal{K}_t) \geq \tilde{\pi}_{ft}^{(phone)}(\mathcal{J}_{ft} \backslash j, \mathcal{J}_{-ft}, \mathcal{K}_t) + C_{jt}, \tag{17}$$

and for any phone $j \notin \mathcal{J}_{ft}$,

$$\tilde{\pi}_{ft}^{(phone)}(\mathcal{J}_{ft}, \mathcal{J}_{-ft}, \mathcal{K}_t) \geq \tilde{\pi}_{ft}^{(phone)}(\mathcal{J}_{ft} \cup j, \mathcal{J}_{-ft}, \mathcal{K}_t) - C_{jt}. \tag{18}$$

Therefore, we yield an upper bound of the fixed cost for any phone $j \in \mathcal{J}_{ft}$:

$$C_{jt} \leq \tilde{\pi}_{ft}^{(phone)}(\mathcal{J}_{ft}, \mathcal{J}_{-ft}, \mathcal{K}_t) - \tilde{\pi}_{ft}^{(phone)}(\mathcal{J}_{ft} \backslash j, \mathcal{J}_{-ft}, \mathcal{K}_t) \tag{19}$$

and lower bounds for any phone $j \notin \mathcal{J}_{ft}$:

$$C_{jt} \geq \tilde{\pi}_{ft}^{(phone)}(\mathcal{J}_{ft} \cup j, \mathcal{J}_{-ft}, \mathcal{K}_t) - \tilde{\pi}_{ft}^{(phone)}(\mathcal{J}_{ft}, \mathcal{J}_{-ft}, \mathcal{K}_t). \tag{20}$$

Intuitively, for a product in the market, its fixed costs should be bounded from above, and conversely, the fixed cost of a potential product not in the market is bounded from below. We denote the upper bound in (19) and the lower bound in (20) by C_{jt}^U and C_{jt}^L, respectively.

Table 6 shows the quantiles of the estimated C_{jt}^U for products in the data and C_{jt}^L for potential products not in the data. We define the set of potential products for each firm in Appendix B.2. For phones in the data, the median upper bound of fixed costs is 755 million INR. For potential products not in the data, the median lower bound of fixed costs is 27 million INR. Fixed costs include any costs associated with including a phone in a firm's product portfolio that are invariant to the quantity of the phone sold. They explain why cell phone firms offer a limited number of phones. On average, a cell phone firm in our data sells 7 phones simultaneously.

Table 6: Estimated Fixed Cost Bounds (Million INR)

Quantile	25%	50%	75%
Upper Bound for Phones in the Data	238	755	2,167
Lower Bound for Phones not in the Data	0.52	27	376

4.3 Carrier Network Expansion Entry Costs

In studying carriers' network expansion decisions, we focus on 12 telecommunications regions in India to keep the estimation computationally feasible. These 12 regions represent 66.8% of the total population and include all 3 Metro regions, all 5 Category-A regions, and the 4 largest Category-B regions.[10]

We also restrict the action space of each carrier. In each period t, carrier c chooses a subset of regions where it has not deployed its 4G network to expand into, i.e., it chooses $a \subseteq \mathcal{R} \backslash \mathcal{R}_{ct}$. The unrestricted action space thus consists of $2^{\#\mathcal{R} \backslash \mathcal{R}_{ct}}$ possible subsets. This cardinality can be as large as $2^{12} = 4096$. To reduce the size of the action space, we impose the following two restrictions, both of which are consistent with the observed data. First, a carrier will not expand into a Category B region unless it has deployed its 4G networks in a Metro or a Category A region. Second, except for Jio, which enters all regions at once, a carrier will not enter more than two Metro regions at a time, not more than three Category-A regions at a time, and not more than three Category-B regions at a time. Moreover, Airtel and Idea will not enter more than four regions (across categories) at a time.

We parameterize the entry cost of network expansion as a function of the total market size of the newly entered regions, i.e., $f_c(a_{ct}, \theta) = \theta_c \sum_{r \in a_{ct}} M_{rt}$, and allow the coefficient θ_c to be carrier-specific. The parameters to be estimated include these entry cost parameters $(\theta_1, ..., \theta_4)$ and the standard deviation of the action-specific shock (ϕ). Let $\theta = (\theta_1, ..., \theta_4, \phi)$.

We estimate θ using the maximum likelihood approach. The likelihood function is

$$\mathcal{L}(\theta) = \prod_{c=1,...,4, t=1,...,T} \Pr_{ct}(a_{ct} | \mathcal{R}_t, \theta), \tag{21}$$

where $\Pr_{ct}(a_{ct} | \mathcal{R}_t, \theta)$ is the equilibrium choice probability in (16).

We compute the likelihood function in two steps. First, we follow the heuristic algorithm developed in Fan and Yang (2020) to compute the equilibrium of the static product choice and pricing game for a given network structure $(\mathcal{R}_t)$, and then we plug the equilibrium

[10]They are Delhi, Kolkata, Mumbai (Metro regions), Andhra Pradesh & Telangana, Gujarat & Daman & Diu, Karnataka, Maharashtra & Goa, Tamil Nadu (Category-A regions), Madhya Pradesh & Chhattisgarh, Rajasthan, Uttar Pradesh East, and West Bengal (Category-B regions).

into a carrier's profit function to obtain the period profit for each carrier $\Pi_{ct}(\mathcal{R}_t)$. These calculations are done "off-line," i.e., before we search for parameters θ to maximize the likelihood function. Second, and then, for each trial of the entry cost parameters θ, we solve the equilibrium of the dynamic network expansion game $\Pr_{ct}(a_{ct}|\mathcal{R}_t, \theta)$ by backward induction. We set the discount factor to be 0.9740, which amounts an annual discount rate of 0.9. We follow a strategy similar to that in Sweeting (2013) to deal with the large state space problem. See Appendix B for more details.

5 Counterfactual

We conduct two sets of counterfactual simulations. In all simulations, we consider the 2G and 3G networks as well as the potential products of each cell phone firm to be exogenous. We recompute the equilibrium of the dynamic network expansion game, as well as the equilibrium product choice and prices.

In the first counterfactual simulation, we quantify the effect of a policy banning low-cost Chinese cell phones. The Indian government is currently considering banning low-cost Chinese phones priced below INR 12,000 in an effort to push large Chinese cell phone firms out of the lower end of its cell phone market. In 2018Q2, for example, 70% of Chinese phones are priced below 12,000 INR. Therefore, such a policy would have a large impact.

In the second set of counterfactual simulations, we quantify the effects of protectionism in subsidy designs. Specifically, we consider two subsidy policies to accelerate 4G deployment in India. In the first policy, all 4G phones, both domestic and international, are eligible for subsidies. In the second policy, only Indian 4G phones are eligible for subsidies. We refer to the first policy as the "unrestricted subsidy policy" and the second as the "protectionist subsidy policy." We compare the effects of these two policies. In particular, we focus on domestic welfare, which depends on consumer surplus, domestic producer surplus, and subsidy expenditure. In terms of the form of the subsidies, we consider both a consumption subsidy (to reduce the effective price for consumers) and a fixed-cost subsidy (to reduce the fixed costs associated with a phone for firms).

In each counterfactual simulation, we examine the cross-market spillover effect by focusing on the evolution of the number of regions and population covered by 4G networks. Due to the estimated higher markups for international firms' 4G phones and the estimated complementarity between 4G phones and 4G phones, we expect a slower expansion of 4G network coverage in the first counterfactual scenario compared to the data and under the "protectionist subsidy policy" than under the "unrestricted subsidy policy" in the second set of counterfactual simulations.

We study the within-market spillover effects by examining the evolution of the number and sales of 4G phones in India with that in the data. Due to the slower rollout of the 4G network and the complementarity between the two markets, we expect a later introduction and slower growth of 4G phones in the cell phone market in the first counterfactual scenario compared to the data and under the "protectionist subsidy policy" than under the "unrestricted subsidy policy" in the second set of counterfactual simulations.

We also quantify welfare. In terms of consumer surplus, both the slower expansion of 4G network coverage and the slower development of the 4G phone market reduce consumer surplus. In terms of carrier profits, due to the complementarity between the two markets, carriers are expected to earn lower profits in the first counterfactual scenario compared to the data and under the "protectionist subsidy policy" than under the "unrestricted subsidy policy" in the second set of counterfactual simulations. As for the profits of domestic cell phone firms, there are two countervailing forces: on the one hand, they face less or weaker competition when Chinese cell phone firms are disadvantaged; on the other hand, they do not enjoy the within-market spillover effect. If the latter is large enough, we expect their profits to fall.

6 Conclusion

This paper studies indirect network effects between two complementary markets and quantifies a new channel through which international competition can benefit consumers. In this channel, the presence of international firms in one market promotes the development of a complementary market, which in turn encourages product entry by domestic firms in the first market. Consumers benefit from rapid development in the complementary market and from greater product variety in the first market. We empirically identify four features of the Indian mobile phone industry that support this channel. First, 4G phones and 4G networks are complementary. Second, international cell phone firms enjoy higher markups when selling 4G phones. Third, the marginal costs of cell phones decline over time. Fourth, Indian cell phone firms have a cost advantage in producing low-quality phones. These features give rise to within-market spillovers from international cell phone firms to domestic firms and cross-market spillovers to the wireless service market, resulting in positive welfare effects for consumers. We use counterfactual simulations to quantify these effects, examine a proposed ban on low-cost phones by Chinese cell phone firms, and study the effects of protectionism in subsidy designs.

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Appendices

A Summary Statistics

In this section, we report summary statistics on cell phones, plans, and telecommunication regions.

Table A.1 reports the summary statistics for 3G and 4G cell phones. An observation is a phone/year combination between 2011 and 2014 and a phone/quarter between 2015Q1 and 2018Q2. We divide annual sales between 2011 and 2014 by 4 in reporting sales statistics.

Table A.1: Summary Statistics: Cell Phones

	Mean	S.D.
Price (INR)	11,297	11,118
Sales (Million)	0.35	0.55
Screen Size (Inch)	4.79	0.82
Camera Resolution (Megapixel)	8.47	4.29
Internal Memory (GB)	17.08	17.04
RAM (GB)	1.66	1.11
Battery Capacity (Ah)	2.50	0.83
Number of Obs	1,106	

Table A.2 reports the summary statistics for the wireless service plans. An observation is a plan/quarter combination.

Table A.2: Summary Statistics: Plans

	Mean	S.D.
Monthly Price (INR)	121	41
Sales (Million)	2.83	3.58
Number of Obs	489	

Table A.3 reports the summary statistics for the 22 telecommunication regions. Population data comes from the 2011 census. We use the per-capita state domestic product in a region obtained from the Reserve Bank of India as a proxy for income at the regional level. The last column reports the average income in 2015 INR (averaged over time) for each region.

Table A.3: Summary Statistics: Regions

Region	Category	Population	Avg Income
Delhi	Metro	16,787,941	296,709
Kolkata	Metro	4,486,679	225,688
Mumbai	Metro	12,478,447	495,791
Andhra Pradesh & Telangana	A	84,580,777	118,678
Gujarat & Daman & Diu	A	60,682,939	137,067
Karnataka	A	61,095,297	144,777
Maharashtra & Goa	A	101,354,431	145,467
Tamil Nadu	A	72,147,030	139,201
Haryana	B	25,351,462	163,762
Kerala	B	33,470,534	146,118
Madhya Pradesh & Chhattisgarh	B	98,172,007	66,068
Punjab	B	27,743,338	117,132
Rajasthan	B	68,548,437	81,513
UP(West) & Uttarakhand	B	70,029,994.3	67,823
Uttar Pradesh(East)	B	139,868,638.7	31,698
West Bengal	B	86,789,436	75,704
Assam	C	31,205,576	58,972
Bihar & Jharkhand	C	137,087,586	37,288
Himachal Pradesh	C	6,864,602	132,110
Jammu and Kashmir	C	12,541,302	69,644
North East	C	14,566,612	84,396
Orissa	C	41,974,218	68,541

B Estimation Details

B.1 Demand Estimation

The indirect utility that consumer i gets from buying phone j and plan k at time t is given in (1), copied below:

$$u_{ijkt} = x_{jkt}\beta - \alpha_{it}(p_{jt} + p_{kt}) + \xi_{jt}^{(ph)} + \xi_{kt}^{(pl)} + \varepsilon_{ijkt}.$$

In this utility function, the vector x_{jkt} includes characteristics of phone j (including technology and firm fixed effects, denoted by $x_{jt}^{(ph)}$), characteristics of plan k (including technology and carrier fixed effects, denoted by $x_{kt}^{(pl)}$), a dummy variable $\mathbb{1}(4G_j, 4G_k)$, and a time fixed effect. Therefore, $x_{jkt}\beta = \beta_{0t} + x_{jt}^{(ph)}\beta^{(ph)} + x_{kt}^{(pl)}\beta^{(pl)} + \beta_{44}1(4G_j, 4G_k)$.

We define $\delta_{jt}^{(ph)} = x_{jt}^{(ph)}\beta^{(ph)} + \xi_{jt}^{(ph)}$ and $\delta_{kt}^{(pl)} = \beta_{0t} + x_{kt}^{(pl)}\beta^{(pl)} + \xi_{kt}^{(pl)}$. Conditional on parameters $(\alpha_0, \alpha_1, \sigma_\alpha, \beta_{44})$, we invert out $(\delta_{jt}^{(ph)}, \delta_{kt}^{(pl)})$ by matching model implications of phone and plan market shares to their empirical counterparts $s_{jt}^{(ph)}$ and $s_{kt}^{(pl)}$.[11] Since for any $(\delta_{jt}^{(ph)}, \delta_{kt}^{(pl)})$ that matches the market shares, $(\delta_{jt}^{(ph)} + a, \delta_{kt}^{(pl)} - a)$ for any constant a also does so, we normalize $\delta_{jt}^{(ph)}$ for one product in each time period to be zero.

B.2 Definition of Potential Products

We define the potential products for each cell phone firm as follows.[12] Since each product is a triple of (firm, technology, quality), we define the set of potential products for different technologies separately.

Potential 3G Products For each cell phone company f, let $\underline{q}_f^{3G}$ represent the minimum quality of all its 3G phones in the sample and $\overline{q}_{ft}^{3G}$ represent the maximum quality of all its 3G phones before (including) time t.

For each cell phone firm f, we define its potential 3G products at time t as follows.

1. Define a vector of grid points between $\underline{q}_f^{3G} - 5$ and $\overline{q}_{ft}^{3G} + 5$ with increment 1.

2. Remove a point from this vector if the quality of an observed 3G phone of firm f (i.e., q_j for $j \in \mathcal{J}_{ft}$) is within 0.5 of that point.

3. Define the set of potential 3G products for cell phone firm f at time t as the union of the remaining points and the qualities of its observed 3G products $\{q_j : j \in \mathcal{J}_{ft}\}$.

In our data, some international cell phone firms never sold 3G phones in India. For these firms, both $\underline{q}_f^{3G}$ and $\overline{q}_{ft}^{3G}$ are not defined, and we define this set as empty. Moreover, all international cell phone firms stopped selling 3G phones after 2017Q1. Therefore, we define this set as empty after 2017Q1 for all international cell phone firms.

Potential 4G Products To define the set of potential 4G products for each firm f, we define $\underline{q}_f^{4G}$ and $\overline{q}_{ft}^{4G}$ analogously and follow the same steps 1-3 as above.

[11] For the JioPhone bundles (indexed by b), we define $\delta_{bt} = x_{bt}^{(ph)}\beta^{(ph)} + x_{bt}^{(pl)}\beta^{(pl)} + \xi_{bt}$ and observe market share s_{bt} at the bundle level.

[12] We treat Apple's iPhones and Jio's JioPhones as exogenous and thus do not need to define their potential products. Apple does not produce cell phones specifically for India. Its product portfolio is largely driven by the global market. As for JioPhones, Jio did not introduce them when it launched its 4G network largely for exogenous reasons.

For periods prior to 2013Q1 (when 4G phones were first introduced in India), we define an international firm's set of potential 4G products as its set in 2013Q1. For periods prior to 2015Q2 (when the first Indian 4G phone was introduced), we define an Indian firm's set of potential 4G products as its set in 2015Q2.

B.3 Details on Solving the Dynamic Network Expansion Game

Computing the equilibrium of the dynamic network expansion game is subject to the challenge of a large state space. The state variable in the dynamic expansion game is $\mathcal{R}_t = (\mathcal{R}_{1t}, ..., \mathcal{R}_{4t})$, where $\mathcal{R}_{ct}$ is the set of regions in which carrier c offers 4G services in period t. Therefore, $\mathcal{R}_{ct}$ is either the empty set or the full set $\mathcal{R}$ for Jio and a subset of $\mathcal{R}$ for the other three carriers. Since the full set consists of 12 regions, there are $(2^{12})^3 \times 2$ possible values for the state variable $\mathcal{R}_t$. Although the two restrictions on the action space explained in Section 4.3 reduce the state space, it is still large, especially for earlier periods.

To address this issue of a large state space, we follow Sweeting (2013) to compute the value function for a subset of possible values of the state variable and approximate the value function for other values of the state variable with a linear function of a set of summary statistics of the state variable. Specifically, for each period t, we randomly draw a set of values for $\mathcal{R}_t$: $\{\mathcal{R}_t^d, d = 1, ..., D\}$. We also include the observed values of $\mathcal{R}_t$ in this set. We compute the value function $V_{ct}(\mathcal{R}_t^d, \theta)$ for each d. We then consider a mapping from the original state variables $\mathcal{R}_t$ to a set of low-dimensional statistics $s_t(\mathcal{R}_t)$ and regress $V_{ct}(\mathcal{R}_t^d, \theta)$ on $s_t(\mathcal{R}_t^d, \theta)$. We do this separately for each carrier c and for each time period t. Let $\hat{\lambda}_{ct}(\theta)$ be the estimated coefficients for carrier c time t. We approximate the value function $V_{ct}(\mathcal{R}_t, \theta)$ for each $\mathcal{R}_t$ by $s_t(\mathcal{R}_t)\hat{\lambda}_{ct}(\theta)$.

To compute $V_{ct}(\mathcal{R}_t, \theta)$, we need to first compute $\Pi_{ct}(\mathcal{R}_t)$. The per-period profit function $\Pi_{ct}(\mathcal{R}_t)$ is equivalently denoted by $\Pi_{ct}(\mathcal{K}_t) = \widetilde{\pi}_{ct}^{(carrier)}(\mathcal{J}_t^*(\mathcal{K}_t), \mathcal{K}_t)$ in (12), where $\widetilde{\pi}_{ct}^{(carrier)}(\mathcal{J}_t, \mathcal{K}_t) = E_{(\boldsymbol{\xi}_t, \boldsymbol{\omega}_t)}\left[\pi_{ct}^{(carrier)}(\mathcal{J}_t, \mathcal{K}_t, \boldsymbol{\xi}_t, \boldsymbol{\omega}_t)\right]$ in (10). Therefore, we solve the equilibrium of the product choice game, which gives us the equilibrium product portfolios $\mathcal{J}_t^*(\mathcal{K}_t)$ and the equilibrium prices $p_{jt}^*(\mathcal{J}_t, \mathcal{K}_t, \boldsymbol{\xi}_t, \boldsymbol{\omega}_t)$ and $p_{kt}^*(\mathcal{J}_t, \mathcal{K}_t, \boldsymbol{\xi}_t, \boldsymbol{\omega}_t)$, the latter of which allow us to compute the carrier profit at the equilibrium prices for any given demand and marginal cost shocks, i.e., $\pi_{ct}^{(carrier)}(\mathcal{J}_t, \mathcal{K}_t, \boldsymbol{\xi}_t, \boldsymbol{\omega}_t)$. We follow the algorithm in Fan and Yang (2020) to solve the equilibrium of the product choice game and do so before the dynamic estimation.