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

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Abstract

This paper studies indirect network effects on firm entry and product variety. Specifically, we quantify how the presence of technologically more advanced international firms in one market helps the development of the other market by encouraging entry (a cross-market spillover effect), which, in turn, affects domestic firms in the first market by increasing their profits from new products (a within-market spillover effect), and more importantly, how consumers benefit from both spillovers. Our context is the Indian mobile phone industry during the 4G rollout. The industry consists of two complementary markets: the handset market, where international firms play a large role, and the wireless service market. Using data on sales, prices, and product availability in these two markets, we estimate a structural model of consumer demand, carriers' 4G network expansions, and handset firms' product choices. Our estimates yield four findings supporting the spillover effects. Using counterfactual simulations, we quantify how the presence of international handset firms accelerates 4G network deployment, increases 4G handset variety, and benefits consumers.

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

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1 Introduction

Indirect network effects occur when the value of a product in one market depends on the availability, prices, and qualities of products in another market. They often result in interdependence between two markets. For example, growth, subsidies, and product compatibility in one market can affect demand and firm prices in the other market.

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 benefits domestic firms in the open market by increasing their profits from new products. In other words, the international firms in one market has a cross-market spillover effect on the other market as well as a within-market spillover effect on the domestic firms in the same market. Importantly, consumers benefit from firm entry and increased product variety due to these spillover effects.

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

The spillovers we study in this paper operate through the following three-step channel: First, because international handset firms have technological advantages over Indian handset firms and have already developed 4G handsets for international markets, their presence makes it more likely that 4G handsets will be available in the Indian handset market. In anticipation of this, carriers have higher incentives to start building their 4G networks compared to a scenario without these international handset firms. We call this a "cross-market spillover effect": the presence of technologically more advanced firms in one market affects development in a complementary market. Second, as the cost of producing 4G handsets declines over time, more and better 4G handsets are introduced to the market, providing incentives for carriers to further expand their 4G networks. Again, this is a cross-market spillover effect. Third, as 4G network coverage expands, Indian handset makers may find it profitable to sell 4G handsets themselves. Thus, the international handset firms have a "within-market spillover effect" on the domestic handset firms. As a result of these spillover effects, consumers benefit from a faster rollout of 4G networks and a greater variety of 4G handsets.

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

We estimate the model using a newly compiled dataset on both the handset and wireless service markets in India. Specifically, we obtain data on prices, characteristics, and sales of both handsets and plans at the national level between 2011 and 2018. We also hand-collected data on carrier networks at the regional level for each quarter during the same period. During this sample period, 3G networks were stable, while 4G networks were being established and expanded in India. Finally, we supplement the data with information on 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 handset on a 4G network, even though 4G handsets are compatible with 2G or 3G networks. This finding suggests that 4G handsets and 4G networks are complementary, so that market structure in the handset market affects carriers' 4G network deployment decisions and, conversely, 4G network coverage affects handset manufacturers' product and pricing decisions. Second, the fixed costs of selling 4G handsets are lower for international handset firms than for Indian firms. Such cost advantages of international handset firms in selling 4G handsets imply that they are more likely to introduce 4G handsets, making it more profitable for carriers to start building their 4G networks. Third, the marginal cost of producing 4G handsets declines over time. The downward trend in marginal cost can lead to lower prices and more 4G handsets, making the purchase of a 4G handset more attractive to consumers and, in turn, providing further incentives for carriers to expand their 4G networks over time. Fourth, while Indian handset manufacturers are less efficient at producing high-quality handsets, they face lower costs for producing low-quality handsets, suggesting that there is room for Indian handset manufacturers to introduce low-end 4G handsets 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 handset firms can potentially benefit from the faster 4G network rollout resulting from the presence of international handset firms. Taken together, these four findings support the spillover effects from international handset firms to domestic Indian handset firms and to the wireless services market.

To quantify both the within-market and cross-market spillovers and welfare effects, we conduct two sets of counterfactual simulations based on the estimated model. In one counterfactual simulation, we remove international handset firms. In the other simulation, we transform international handset firms into domestic firms by setting their firm fixed effects in the demand model to the average of their Indian counterparts and lowering their fixed costs of selling 4G handsets.

We also conduct a third counterfactual simulation to quantify the impact of a policy to ban low-cost Chinese handsets. The Indian government is considering banning low-cost Chinese handsets priced below INR 12,000. This initiative is aimed at eliminating Chinese handset firms from the lower end of the Indian handset market.

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 handsets with that in the data to quantify the within-market spillover effect. We do not yet have the counterfactual simulation results. Intuitively, we expect a slower expansion of 4G network coverage in the counterfactual scenarios because of the estimated cost advantages of international handset firms in selling 4G phones and the estimated complementarity between 4G phones and 4G handsets. Consequently, we expect later adoption and slower growth of 4G handsets in the handset market due to the slower 4G network rollout.

By studying two complementary markets simultaneously, this paper contributes to the literature on 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 impact of exclusivity in the game hardware and software markets, Li (2019) on the effect of incompatible charging standards on the electric vehicle and charging station markets, and Springel (2021) on subsidies 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 one market helps the development of the complementary market and, in turn, affects domestic firms in the first market as well as consumers.

By studying both handset firms' product choices and carriers' network expansion decisions, this paper is also related to the literature on endogenous product choice and firm entry. Examples in this literature include Draganska, Mazzeo, and Seim (2009), Fan (2013), Eizenberg (2014), Wollmann (2018), Chaves (2020), Fan and Yang (2020), and Fan and Yang (2022) for endogenous product choice and Collard-Wexler (2013), Dunne, Klimek, Roberts, and Xu (2013), Sweeting (2013), Fan and Xiao (2015), and Mohapatra and Zhang (2020) for dynamic entry games. We embed a static handset product choice model into a dynamic network expansion model to study firms' decisions in both markets and the interdependence between them.

Finally, by studying the effect of opening a market to international competitors, this paper is related to the trade literature on the effect of foreign competition on domestic markets. For example, studying Turkey, Côte d'Ivoire, and India, respectively, Levinsohn (1993), Harrison (1994), and Krishna and Mitra (1998) find that increased foreign competition increases market efficiency and reduces firm markups. See Tybout (2008) for a survey on this topic. Focusing mainly on productivity, another strand of the literature studies the externalities of foreign direct investment from developed countries to domestic firms in developing countries. The empirical evidence on such externalities appears to be mixed. See Harrison and Rodríguez-Clare (2010) for a comprehensive survey. We add to this literature with a study in which foreign competition can potentially benefit domestic firms by helping the development of a complementary market. More importantly, foreign competition in one market increases product variety in both markets, benefiting consumers.

From a policy perspective, this paper contributes to the debate on whether international handset firms are harming domestic handset firms in India. There have been complaints in the media that international handset firms, especially Chinese handset firms, introduced their 4G phones before 4G networks were widespread in India, crowding out domestic handset makers. In this paper, we show that the early entry of 4G handsets by international handset 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 handset in the handset market, again due to the indirect network effect. As a result, 4G networks are rolled out faster and more 4G handsets are offered. Both of these effects benefit consumers, although the net effect on domestic handset 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 affects firms' product choices, 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 foreign firms.

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 provide a brief summary of the industry, describe the data, and present data patterns for the handset market and the wireless services market.

2.1 Industry Background

The Indian mobile industry consists of two markets: the handset market and the wireless service market. A consumer must purchase a handset and a network plan in order to enjoy wireless service. Unlike in the US, consumers in India purchase a handset and a network plan separately. This is true for the majority of handset and plan sales in our sample. One exception is Jio, a carrier that sells stand-alone plans that any handset owner can purchase. Between 2015 and 2017, Jio also sold stand-alone handsets under the brand name LYF. Since 2017Q3, Jio has been selling handset/plan bundles, where the handsets (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 handset market consists of both domestic and international handset 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 handset 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 before the start of our sample period.

Our handset data contain information on sales, prices, and handset characteristics. The data cover all handsets sold in India between 2011 and 2018. We keep a handset firm in our sample if its 3G handset sales are at least 5% of all 3G handset sales and its 4G handset sales are at least 1% of all 4G handset sales. For each handset in our data, we observe its manufacturer identity, technology (a 2G, 3G, or 4G handset), screen size, camera resolution, memory, storage, and battery capacity. The 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 between 2015 and 2018 to the quarterly level to be consistent with the frequency of 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) for each region and 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. While a carrier may offer multiple plans of the same technology, we do not observe sales or prices at the plan level. For simplicity, we refer to a carrier/technology combination as a plan from here on.

We consider the population above 15 years of age as potential buyers. According to the 2011 Census, the population above 15 years of age accounts for 69% of the total population in India. We obtain the annual national population data from the United Nations Population Division and the population share in each region from the 2011 Census. We combine the regional share data with the annual national population data and multiply their product by 69% to obtain the market size in each region/year combination. We obtained the annual "Net State Domestic Product" data 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, or rather, as a shiftor for consumer utility. We use the CPI data to deflate prices and income to 2015 INR.[1]

[1] CPI data is taken from FRED economic data (https://fred.stlouisfed.org/series/INDCPIALLAINMEI).

2.3 Data Patterns

We present summary statistics in an appendix section. In this section, we highlight three data patterns regarding the handset and the wireless service markets.

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

Table 1: Handset Firms and Sales Shares

Origin	Firm	Sales Share	Total
Indian	Intex	3.3%	
Indian	Lava	3.2%	
Indian	LYF	15.7%	
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	1.8%	
Non-Asian	Microsoft/Nokia	6.1%	8%

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

Second, while Indian handset firms occupy the lower end of the market, international firms dominate the higher end. Table 2 shows the sales shares of handset firms by origin and by price range for 4G handsets. Specifically, we consider three price ranges defined by tertiles. The table shows that while Indian handset firms account for 100% of total 4G handset sales in the low price range, the share drops dramatically to 26% and 1% in the medium and high price ranges. Other Asian handset firms are only present in the mid- and high-price segments, with sales shares of 74% and 91%, respectively. Non-Asian companies are only present in the high-price segment, with a total share of 7% in this market segment.

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

	Sales Share		
Origin	Low-Price	Medium-Price	High-Price
Indian	100%	26%	1%
Other Asian	-	74%	91%
Non-Asian	-	-	7%

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

Third, 4G handset sales increased and 4G network coverage expanded over time. The left panel of Figure 1 presents the number of regions covered by 4G networks over time. 4G network coverage in India started in 2013,[2] gradually expanded among urban regions followed by rural regions, and finally reached all 22 regions in 2016Q3. The right panel shows 4G handset sales by country of origin over time. We can see that with the expansion of the 4G network, the sales of 4G handsets increased over time. Indian handset firms entered the 4G market later than international handset firms. Their sales started at a low level initially and skyrocketed in 2017.

In summary, our data shows that international firms play a big role in the handset market. They started selling 4G handsets first. The growth of their 4G handset sales and 4G network rollout coincided. Indian handset manufacturers caught up towards the end of the sample when 4G coverage reached all regions.

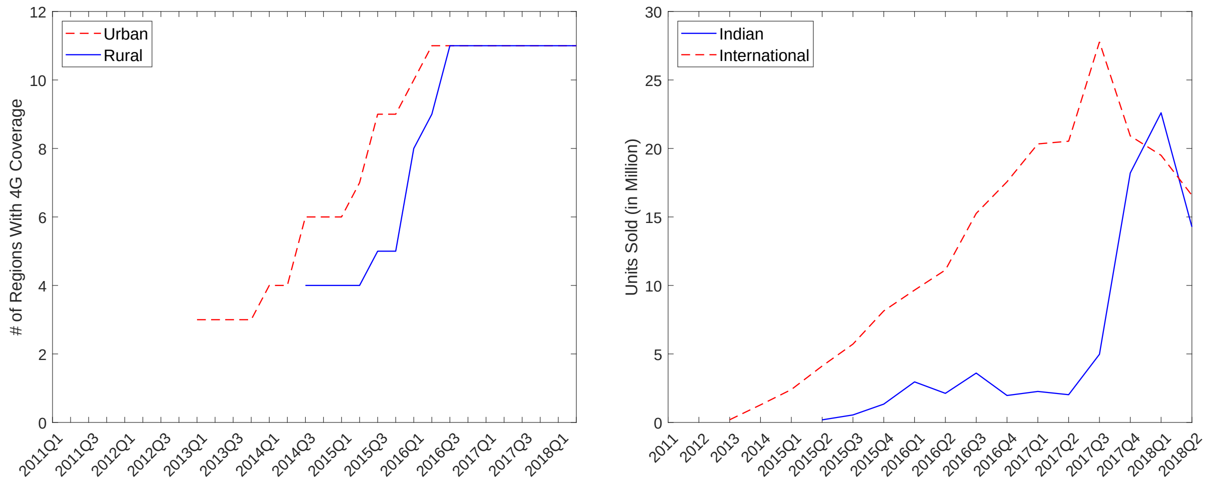
3 Model

To quantify how the presence of technologically more advanced international firms in the handset market affects the development of the wireless service market (the cross-market spillover effect), domestic firms in the handset market (the within-market spillover effect), and consumers (the welfare effect), we develop and estimate a structural model of demand,

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

Figure 1: 4G Network Coverage and 4G Handsets Sales Over Time

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



Notes: The left panel plots the number of urban and rural regions covered by 4G networks over time. The right panel plots the units sold (in millions) of 4G handsets over time by Indian, other Asian, and non-Asian handset 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.

network expansion, product choice, and pricing in the Indian handset and wireless service markets.

3.1 Demand

Demand is described by a discrete-choice model. Consumers choose a handset and a wireless plan, or the outside option of not using a mobile phone. A consumer needs both a handset (indexed by j) and a wireless plan (indexed by k) to use a mobile phone. Let $\mathcal{J}_{rt}^{(p)}$ be the set of wireless plans in region r at time t and $\mathcal{J}_{t}^{(h)}$ the set of handsets on the market at time t. Let $\mathcal{J}_{rt}^{(hp)}$ be the set of handset/plan combinations available to consumers in region r and time t. It includes all (j, k) combinations such that $j \in \mathcal{J}_{t}^{(h)}$ and $k \in \mathcal{J}_{rt}^{(p)}$ except that 3G handsets are not compatible with 4G plans, 2G handsets 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 handset j and wireless plan k at time t:

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

where the vector x_{jkt} includes three sets of covariates. First, it includes a quality index of handset j, which depends on the observable product characteristics x_j as $q_j = x_j\rho$, where ρ are 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 mobile phone market, we assume that consumer utility depends on handset characteristics only through the quality index. This parsimonious functional form allows us to characterize a handset by its quality index and later define potential products based on their quality indices. Second, x_{jkt} includes a dummy variable $1\{4G_j, 4G_k\}$ that takes value 1 if and only if handset j is a 4G handset and plan k is a 4G plan. By including this variable, we allow consumers to derive a differential utility from using a 4G handset on a 4G network over and above the advantages of a 4G handset captured by handset characteristics (including the 4G handset dummy). Third, we include handset technology fixed effects, plan technology fixed effects, handset firm fixed effects, carrier fixed effects, and time fixed effects to capture systematic differences at different levels.

In the utility function (1), p_{jt} is the price of handset j and p_{kt} is the price of plan k.[3] We allow for heterogeneity in consumer price sensitivity: $\alpha_{it} = \alpha + \kappa Inc_r + \sigma v_{it}$, 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 $\xi_{jt}^{(h)}$ and $\xi_{kt}^{(p)}$ to capture unobservable handset and plan characteristics. 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 market share of combination jk in region r at time t is

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

where $\boldsymbol{p}_{rt} = (p_j + p_k, jk \in \mathcal{J}_{rt}^{(hp)})$ and $\boldsymbol{x}_{rt} = (x_{jkt}, jk \in \mathcal{J}_{rt}^{(hp)})$. Similarly, $\boldsymbol{\xi}_{rt}$ contains the collection of $\xi_{jt}^{(h)}$ for handsets compatible with at least one plan in $\mathcal{J}_{rt}^{(p)}$ and the collection of $\xi_{kt}^{(p)}$ for plans in $\mathcal{J}_{rt}^{(p)}$. 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 handset j, we sum the market share in (2) first over all plans that this handset is compatible with in region r and then over regions $r = 1, ..., R$. Similarly, the market share of plan k is the aggregation over all regions and all handsets compatible with that plan. Specifically, let w_r be the population weight of region r in the nation. The market shares of handset j and plan k at time t are, respectively,

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

[3] The price of a plan is the monthly price of a plan multiplied by the average duration 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, respectively (Zeebiz, 2017).

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

where $(\boldsymbol{p}_t, \boldsymbol{x}_t, \boldsymbol{\xi}_t)$ are defined similarly to $(\boldsymbol{p}_{rt}, \boldsymbol{x}_{rt}, \boldsymbol{\xi}_{rt})$ for all handsets and plans in the nation instead of those in a region, and s_{jkrt} is set to 0 for handset and plan combinations jk that are incompatible. 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 handset sales, we also aggregate the market share in (3) across quarters within a year.[4]

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 a dynamic one. In such a dynamic game, each carrier's period profit is determined by a static game in which handset firms choose the set of handsets to sell given the network structure in the country. Intuitively, the greater the 4G network coverage, the greater the profits that handset firms get from selling 4G handsets. 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 handset market and the network service market. In our model, handset firms and carriers also decide the prices of handsets and network plans.

We model the product choice of handset firms as a static problem. Solving 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 to deploy their 4G networks and handset firms choose a subset of their potential products to sell) is computationally prohibitive. 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. More importantly, even though 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 effect at the center of the paper: the presence of international handset firms in the handset market makes it more likely that 4G phones will be sold. In anticipation of this, carriers have higher incentives to roll out their 4G networks compared to a scenario without international

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

handset firms. Over time, any change in the handset market that leads to an increase in 4G handset sales (e.g., lower marginal costs over time) gives carriers incentives to expand their 4G network. Eventually, with greater 4G network coverage, even Indian handset firms may find it profitable to sell 4G handsets.

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, with handset firms choosing products in the first stage and both handset firms and carriers choosing prices in the second stage. We describe these two stages in reverse order.

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

$$\max_{\{p_{jt}:j\in\mathcal{J}_{ft}^{(h)}\}} \sum_{j\in\mathcal{J}_{ft}^{(h)}} s_{jt}^{(h)}(\boldsymbol{p}_t, \boldsymbol{x}_t, \boldsymbol{\xi}_t; \mathcal{J}_t^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R})(p_{jt} - c_{jt}^{(h)}), \tag{5}$$

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

$$log(c_{jt}^{(h)}) = \gamma_0 + \gamma_1 \mathbb{1}(Indian)_j + (\tau_0 + \tau_1 \mathbb{1}(Indian)_j)q_j + (\eta_0 + \eta_1 \mathbb{1}(Indian))t + \omega_{jt}^{(h)}. \tag{6}$$

In this specification, the marginal cost depends on the quality of a handset. We allow both the level of the marginal cost and its slope with respect to quality to differ between international and Indian handset firms. We also include a time trend and allow it to be different for international and Indian handset firms. Finally, $\omega_{jt}^{(h)}$ is the marginal cost shock.

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

$$\max_{\{p_{kt}:k\in\mathcal{J}_{ct}^{(p)}\}} \sum_{k:k\in\mathcal{J}_{ct}^{(p)}} s_{kt}^{(p)}(\boldsymbol{p}_t, \boldsymbol{x}_t, \boldsymbol{\xi}_t; \mathcal{J}_t^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R})(p_{kt} - c_{kt}^{(p)}), \tag{7}$$

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

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 service) and a set of 4G handsets under the brand name LYF. Therefore, Jio's problem is to choose both the price of its plan (p_{kt}) and the prices of the LYF handsets ($\{p_j : j \in \text{LYF}_t\}$) to maximize the total profit from both handset sales and plan sales. Afterwards, Jio sold both its network plan (which can be combined with any handsets) and handset/plan bundles, where the handsets (called JioPhones) can only be used on Jio's network. In this case, Jio's problem is to choose both the stand-alone plan price (p_{kt}) and the prices for the bundles ($p_j : j \in \text{Jiophone}_t$) to maximize the total profit from selling the stand-alone plan and the bundle. In sum, the profit-maximization problem is

$$\max_{p_{kt}, \{p_{jt}: j \in \mathcal{J}_{ft}^{(h)}\}} \quad s_{kt}^{(p)}(\boldsymbol{p}_t, \boldsymbol{x}_t, \boldsymbol{\xi}_t; \mathcal{J}_t^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^R)(p_{kt} - c_{kt}^{(p)}) + \sum_{j: j \in \mathcal{J}_{ft}^{(h)}} s_{jt}^{(h)}(\boldsymbol{p}_t, \boldsymbol{x}_t, \boldsymbol{\xi}_t; \mathcal{J}_t^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^R)(p_{jt} - c_{jt}^{(h)}), \tag{8}$$

where $\mathcal{J}_{ft}^{(h)}$ represents either the LYF handsets or JioPhones and $c_{jt}^{(h)}$ represents either the marginal cost of a LYF handset or that of the JioPhone bundles.

Let $p_{jt}^*(\boldsymbol{x}_t, \boldsymbol{\xi}_t, \boldsymbol{\omega}_t; \mathcal{J}_t^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^R)$ and $p_{kt}^*(\boldsymbol{x}_t, \boldsymbol{\xi}_t, \boldsymbol{\omega}_t; \mathcal{J}_t^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^R)$ be the equilibrium prices for handset j and plan k, where $\boldsymbol{\omega}_t$ is the collection of marginal cost shocks.

At the product choice stage, handset firms observe each carrier's network and thus the set of plans available in each region $\mathcal{J}_{rt}^{(p)}$. Each handset firm f is endowed with a set of potential handsets $\mathcal{H}_{ft}$ and decides on the set of handsets to offer, i.e. $\mathcal{J}_{ft}^{(h)} \subseteq \mathcal{H}_{ft}$, in order to maximize its expected profit, which is the difference between the expected variable profit and the fixed costs associated with offering a particular set of handsets. The expectation is taken over demand and marginal cost shocks that are realized at the pricing stage.

To derive the expected variable profit for a handset firm, we plug the equilibrium prices $p_{jt}^*(\boldsymbol{x}_t, \boldsymbol{\xi}_t, \boldsymbol{\omega}_t; \mathcal{J}_t^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^R)$ and $p_{kt}^*(\boldsymbol{x}_t, \boldsymbol{\xi}_t, \boldsymbol{\omega}_t; \mathcal{J}_t^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^R)$ into the profit of handset firm f in (5), take the expectation over the demand and marginal cost shocks ($\boldsymbol{\xi}_t, \boldsymbol{\omega}_t$), and multiply the expectation by the market size. In the end, the expected variable profit depends on the set of handsets available at the time $\mathcal{J}_t^{(h)}$ and the set of plans in each region $\{\mathcal{J}_{rt}^{(p)}\}_{r=1}^R$. Since $\mathcal{J}_t^{(h)} = \{\mathcal{J}_{ft}^{(h)}\}_{f=1}^F$, where F is the number of handset firms, we denote handset firm f's expected variable profit by $\pi_{ft}^{(handset)}(\{\mathcal{J}_{ft}^{(h)}\}_{f=1}^F, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^R)$. To isolate what firm f can choose (its own product portfolio) from what it cannot choose (its opponents' product portfolio), we rewrite firm f's expected variable profit as $\pi_{ft}^{(handset)}(\mathcal{J}_{ft}^{(h)}, \mathcal{J}_{-ft}^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^R)$ in firm f's profit-maximization problem below.

Handset firm f's profit-maximization problem at the product choice stage is, therefore,

$$\max_{\mathcal{J}_{ft}^{(h)} \subseteq \mathcal{H}_{ft}} \pi_{ft}^{(handset)}(\mathcal{J}_{ft}^{(h)}, \mathcal{J}_{-ft}^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^R) - \sum_{j \in \mathcal{J}_{ft}^{(h)}} C_{jt}, \tag{9}$$

where C_{jt} is the fixed cost of offering handset j.

The equilibrium of this stage is each firm's handset portfolio given carriers' networks $\{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R}$. Let $\{\mathcal{J}_{ft}^{(h)*}(\{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R})\}_{f=1}^{F}$ represent the equilibrium handset portfolios for the F handset firms in the market.

At this equilibrium, a carrier's expected profit is

$$\Pi_{ct}(\{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R}) = \pi_{ct}^{(carrier)}(\{\mathcal{J}_{ft}^{(h)*}(\{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R})\}_{f=1}^{F}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R}), \tag{10}$$

where $\pi_{ct}^{(carrier)}(\{\mathcal{J}_{ft}^{(h)}\}_{f=1}^{F}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R})$ is carrier c's expected variable profit given the handsets at the time and the plans in each region. It is similarly derived as how we derive the expected variable profit for a handset firm, $\pi_{ft}^{(handset)}(\{\mathcal{J}_{ft}^{(h)}\}_{f=1}^{F}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R})$. We then plug the equilibrium handset portfolios $\{\mathcal{J}_{ft}^{(h)*}(\{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R})\}_{f=1}^{F}$ into $\pi_{ct}^{(carrier)}(\{\mathcal{J}_{ft}^{(h)}\}_{f=1}^{F}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R})$ and obtain a function of $\{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R}$, i.e. $\Pi_{ct}(\{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R})$ in (10). This profit function is the period profit in the carrier 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.[5]

We model carriers' 4G network expansion decisions as a finite-period dynamic discrete game. The finite-period assumption is consistent with the nonstationarity of the process: expanding one's 4G network into a region is an absorbing state, and by the end of our sample, all four carriers had entered into almost all the regions studied in the paper.[6]

We first introduce some notation in order 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 $\Pi_{ct}(\mathcal{R}_t)$. Note that a carrier's period profit is originally expressed as a function of the set of plans in each region, i.e., $\Pi_{ct}(\{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R})$ in

[5] 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 mostly operated 2G and 3G networks, and offered limited 4G services before exiting the market in 2018Q2. Similarly, Reliance Communication also mostly operated and offered 2G and 3G services, and declared bankruptcy in 2019.

[6] 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.

equation (10). Since the 2G and 3G networks are treated as exogenous, and whether carrier c offers 4G services in region r determines whether plan "carrier-c/4G technology" is in $\mathcal{J}_{rt}^{(p)}$, the period profit can be equivalently written as a function of each carrier's 4G network.

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 regions it has not entered with 4G services (denoted by $\mathcal{R}\backslash\mathcal{R}_{ct}$). 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. For any carrier, $a_{ct} = \emptyset$ means that this carrier does not expand in this period. Otherwise, this carrier pays the entry cost $f_c(a_{ct}, \theta)$ and its 4G network becomes $\mathcal{R}_{ct} \cup a_{ct}$ in the next period. There is also an action-specific shock $\varepsilon_{ct}(a_{ct})$, which is private information and is realized before a carrier's turn to move in each period.

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 δ be the discount factor. The Bellman equation is

$$V_{ct}(\mathcal{R}_t, \varepsilon_{ct}) = \max_{a_{ct} \in \mathcal{A}_c(\mathcal{R}_{ct})} \{\Pi_{ct}(\mathcal{R}_t) - f_c(a_{ct}, \theta) + \varepsilon_{ct}(a_{ct}) + \delta E_{\varepsilon_{ct+1}} E_{\mathcal{R}_{t+1}}(V_{ct+1}(\mathcal{R}_{t+1}, \varepsilon_{ct+1}) | \mathcal{R}_t, a_{ct})\}. \tag{11}$$

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

$$V_{ct}(\mathcal{R}_t) = \gamma + \phi \ln \Bigg(\sum_{a_{ct} \in \mathcal{A}_c(\mathcal{R}_{ct})} exp\Big(\Big[\Pi_{ct}(\mathcal{R}_t) - f_c(a_{ct}, \theta) + \delta E_{\mathcal{R}_{t+1}}(V_{ct+1}(\mathcal{R}_{t+1}) | \mathcal{R}_t, a_{ct}) \Big] / \phi \Big) \Bigg), \tag{12}$$

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

$$V_{cT+1}(\mathcal{R}_{T+1}) = \frac{\Pi_{cT}(\mathcal{R}_{T+1})}{1-\delta}. \tag{13}$$

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

$$Pr_{ct}(a_{ct}|\mathcal{R}_t) = \frac{exp([\Pi_{ct}(\mathcal{R}_t) - f_c(a_{ct}, \theta) + \delta E_{\mathcal{R}_{t+1}}(V_{ct+1}(\mathcal{R}_{t+1})|\mathcal{R}_t, a_{ct})]/\phi)}{\sum_{a \in \mathcal{A}_c(\mathcal{R}_{ct})} exp([\Pi_{ct}(\mathcal{R}_t) - f_c(a, \theta) + \delta E_{\mathcal{R}_{t+1}}(V_{ct+1}(\mathcal{R}_{t+1})|\mathcal{R}_t, a)]/\phi)}, \tag{14}$$

where $V_{ct}(\mathcal{R}_t)$ is the solution to (12) where the expectation in (12) is taken according to the probability in (14).

4 Estimation and Results

In this section, we explain our estimation procedure and present the estimation results.

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 the parameters using the Generalized Method of Moments. The demand-side moments are constructed by interacting the unobservable demand shocks $\xi_{jt}^{(h)}$ and $\xi_{kt}^{(p)}$ with instrumental variables. We consider two groups of instruments: the 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, 2022). In our demand model, we include a rich set of fixed effects to control for systematic variation across handset technology fixed effects, plan technology fixed effects, handset firms, carriers, and time. Thus, although imperfect, it seems reasonable to assume that the transitory shock specific to a handset or plan is unknown to firms when they make their product choices. To estimate the marginal cost parameters, we first back out marginal costs based on first-order conditions with respect to prices and then regress them on the marginal cost covariates.

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. At the average income of 122,117 INR, the average price coefficient is -7.62 ($= -29.1 + 4.47 \times \log(122.117)$). The standard deviation of the unobservable heterogeneity in price sensitivity

Table 3: Estimation Results: Demand

	Est.	Std. Error
Price (10K INR)	-29.1***	5.57
Price × Income	4.47***	0.89
Price × Normal Draw	0.36***	0.15
Screen Size (Inch)	0.27*	0.17
Camera (MP)	0.09***	0.02
Storage (10GB)	0.41***	0.07
RAM (GB)	0.39***	0.15
Battery Capacity	0.32***	0.11
$\mathbb{1}$(4G Handset)× $\mathbb{1}$(4G Network)	3.24***	0.82
Handset Technology FE	Yes	
Plan Technology FE	Yes	
Handset 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 handset characteristics in the quality index, we report $\beta_q \rho_l$ where β_q is the coefficient of quality in the utility function and ρ_l is the weight of the l^{th} characteristic in the quality index.

is about 5% of this average price coefficient. We also find that consumers prefer handsets with larger screens, higher camera resolution, more storage, more RAM, and higher battery capacity. For example, increasing the storage from 64GB to 128GB is equivalent to a price decrease of about 3400 INR on average, which is about a quarter of the average price of a 4G handset.

Consumers also gain more utility from using a 4G phone on a 4G network. The estimated coefficient of $\mathbb{1}$(4G Handset) × $\mathbb{1}$(4G Network) is 3.24, equivalent to a willingness to pay of 4,248 INR given the average price coefficient. Consumers' preference for using a 4G handset on a 4G network (even though 4G handsets are compatible with 2G and 3G networks) implies complementarity between 4G handsets and 4G networks, which is unsurprising since consumers only enjoy the advanced feature of a 4G handset with a 4G network and the high speed of a 4G network with a 4G handset. The complementarity between 4G handsets and 4G networks leads to the interdependence between the behavior of handset 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 handsets. We find that marginal cost increases with quality ($\hat{\tau}_0 > 0$) and the slope is larger for Indian handset firms ($\hat{\tau}_1 > 0$). We also find that the marginal cost of producing low-quality handsets is lower for Indian firms than for international firms ($\hat{\gamma}_1 < 0$). In other words, Indian firms have a cost advantage in producing low-quality handsets, but their marginal cost rises faster with quality. The finding that Indian firms have a cost advantage in the low-end segment of the handset market supports the within-market spillover effect because it implies that there is room for Indian handset firms to introduce (low-end) 4G handsets if 4G network coverage is large enough later in India's 4G rollout.

Table 4: Estimation Results: Handset Marginal Cost

	Est.	Std. Error
$\mathbb{1}$(Indian) (γ_1)	-1.31***	0.23
Quality (τ_0)	0.10***	0.02
Quality$\times\mathbb{1}$(Indian) (τ_1)	0.16**	0.07
Time Trend $\times\mathbb{1}$(Indian)	-0.05***	0.01
Time Trend $\times\mathbb{1}$(International)	-0.04***	0.01
Jio First Year FE	Yes	

We also find a downward trend in marginal costs. The estimated coefficients of the time trends for Indian and international handsets both have negative signs and are statistically significant. Such a downward trend in the marginal cost of producing a 4G handset supports the continued expansion of the 4G network. This is because declining marginal costs can lead to lower prices and greater product variety for 4G handsets, thereby increasing the attractiveness of 4G handset options for consumers. Given the estimated consumer preference for the combination of a 4G handset on a 4G network, consumers are also more likely to purchase a 4G network plan when available. As a result, carriers have incentives to expand their 4G network over time as the marginal cost of producing 4G handsets declines over time.

4.2 Handset Fixed Costs

We estimate the fixed cost of a handset 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 profit. In other words, for any handset $j \in \mathcal{J}_{ft}^{(h)}$,

$$\pi_{ft}^{(handset)}(\mathcal{J}_{ft}^{(h)}, \mathcal{J}_{-ft}^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R}) \geq \pi_{ft}^{(handset)}(\mathcal{J}_{ft}^{(h)} \backslash j, \mathcal{J}_{-ft}^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R}) + C_{jt}, \tag{15}$$

and for any $j \notin \mathcal{J}_{ft}^{(h)}$,

$$\pi_{ft}^{(handset)}(\mathcal{J}_{ft}^{(h)}, \mathcal{J}_{-ft}^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R}) \geq \pi_{ft}^{(handset)}(\mathcal{J}_{ft}^{(h)} \cup j, \mathcal{J}_{-ft}^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R}) - C_{jt}, \tag{16}$$

where $\pi_{ft}^{(handset)}(\mathcal{J}_{ft}^{(h)}, \mathcal{J}_{-ft}^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R})$ is firm f's expected variable profit, as explained in Section 3.2.1.

Therefore, we yield an upper bound of the fixed cost for any handset in $\mathcal{J}_{ft}^{(h)}$:

$$C_{jt} \leq \pi_{ft}^{(handset)}(\mathcal{J}_{ft}^{(h)}, \mathcal{J}_{-ft}^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R}) - \pi_{ft}^{(handset)}(\mathcal{J}_{ft}^{(h)} \backslash j, \mathcal{J}_{-ft}^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R}) \tag{17}$$

and lower bounds for those not in $\mathcal{J}_{ft}^{(h)}$:

$$C_{jt} \geq \pi_{ft}^{(handset)}(\mathcal{J}_{ft}^{(h)} \cup j, \mathcal{J}_{-ft}^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R}) - \pi_{ft}^{(handset)}(\mathcal{J}_{ft}^{(h)}, \mathcal{J}_{-ft}^{(h)}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R}). \tag{18}$$

Intuitively, for products on the market, their fixed costs should be bounded from above, and conversely, the fixed costs of a product not on the market are bounded from below. We denote the upper bound in (17) and the lower bound in (18) by C_{jt}^{U} and C_{jt}^{L}, respectively.

Table 5 shows the estimated fixed costs by origin and quality segment. For the purposes of this table, we consider the fixed cost of a handset to be $C_{jt} = 0.8C_{jt}^{U}$ for $j \in \mathcal{J}_{t}^{(h)}$ and $C_{jt} = 1.2C_{jt}^{L}$ for $j \notin \mathcal{J}_{t}^{(h)}$. We define the set of potential products for each firm in Appendix A.1. We group the potential handsets into four bins according to their qualities. In each quality bin, we report the median fixed cost across 4G handsets of a given origin (Indian or international). While the quality of a handset in the sample varies from 2 to 51.9, the highest quality among Indian handsets is only 24.8. Therefore, in the four equidistant quality bins, i.e. (2, 14.5], (14.5, 27], (27, 39.4], (39.4, 51.9], Indian handsets are only in the first two bins. From the table, we can see that in the low and low-medium quality segments where both Indian and international handset firms are present, international handset firms have an advantage over their Indian counterparts in terms of the fixed costs of selling a 4G handset.

The finding that international handset firms incur lower costs to sell 4G handsets implies that they are more likely to sell 4G handsets even with relatively low 4G network coverage, providing incentives for carriers to roll out their 4G networks. This is the basis for the cross-market spillover effect, which leads to faster 4G deployment in both markets and benefits consumers.

Table 5: Median Estimated Fixed Cost of 4G Handset by Country Origin and Quality Segment (Million INR)

Origin	Low-Quality	Low-Medium	High-Medium	High-Quality
Indian	983	1458	-	-
International	544	1353	5003	5984

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 account for 66.8% of the total population and include all 3 Metro regions, all 5 Category-A regions, and the 4 largest Category-B regions.[7]

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 either 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 network expansion entry cost as a linear 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

$$\mathcal{L}(\theta) = \prod_{c=1,...,4,t=1,...,T} \Pr_{ct}(a_{ct}|\mathcal{R}_t, \theta), \tag{19}$$

where $\Pr_{ct}(a_{ct}|\mathcal{R}_t, \theta)$ is the equilibrium choice probability in (14).

We compute the likelihood function in two steps. First, we follow the heuristic algorithm

[7] 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).

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 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. 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 follow a strategy similar to that in Sweeting (2013) to deal with the large state space problem. See Appendix A.2 for more details.

5 Counterfactual

We conduct three counterfactual simulations. The first two simulations are quantification exercises. They are designed to quantify the within-market and across-market spillover effects, as well as the welfare effects of international handset firms. The third simulation is a policy analysis in which we quantify the effects of a policy currently under consideration. In all simulations, we consider the 2G and 3G networks as well as the potential products of each handset firm as exogenous.

In the first counterfactual simulation, we remove international handset firms and recompute the equilibrium 4G network of each carrier in each period, as well as the equilibrium set of handsets, handset prices, and plan prices in each period. Intuitively, the absence of international firms in the handset market changes the price competition in both the handset and wireless service markets. Moreover, it directly affects the set of handsets in the market because the handsets produced by these international handset firms disappear with the removal of these firms. It also affects product availability indirectly by influencing the product choices of domestic handset firms. Finally, their absence affects the expansion of 4G networks in the wireless service market, which in turn affects the product choices of Indian handset firms and price competition in these two markets. Our model takes all these effects into account. Thus, our simulation captures all of these effects.

In the second counterfactual simulation, we make all international handset firms domestic. Compared to the first counterfactual simulation, in which the handset market loses many firms and many products, this counterfactual simulation is less of a shock to the industry and also accommodates the possibility that the void created by the absence of the international firms may be filled by the entry of new domestic firms. We operationalize this idea of replacing international firms with domestic firms in two steps. First, we replace their firm fixed effects in the demand model by the average of their Indian counterparts and change their origin from non-Indian to Indian the marginal cost function. Second, we multiply their fixed cost of producing a handset by the ratio of the average fixed cost of handsets produced by domestic firms to the average fixed cost of handsets by international handset firms. We again compute the equilibrium network structure, products, and prices.

In the third counterfactual simulation, we quantify the effect of a policy banning low-cost Chinese handsets. The Indian government is currently considering banning low-cost Chinese handsets priced below INR 12,000 in an effort to push large Chinese handset companies out of the lower end of its handset market.

In each counterfactual simulation, we quantify the cross-market spillover effect by comparing the evolution of the number of regions and population covered by 4G networks with that in the data. Due to the estimated cost advantage of international handset firms in selling 4G handsets and the estimated complementarity between 4G phones and 4G handsets, we expect a slower expansion of 4G network coverage in the counterfactual scenarios.

We quantify the within-market spillover effect by comparing the evolution of the number and sales of 4G handsets in India with that in the data. Due to the slower 4G network rollout and the complementarity between the two markets, we expect a later introduction and a slower growth of 4G phones in the handset market.

We also quantify welfare. In terms of consumer surplus, both the slower expansion of 4G network coverage and the slower development of the 4G handset market reduce consumer surplus. In terms of carriers' profits, due to the complementarity between the two markets, carriers are expected to earn lower profits in the counterfactual scenarios. As for the profits of domestic handset firms, on the one hand, they face less competition in the first counterfactual scenario and weaker competitors in the second counterfactual scenario; 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 handsets and 4G networks are complementary. Second, international handset firms have cost advantages in selling 4G handsets. Third, the marginal cost of producing a 4G handset declines over time.

Fourth, Indian handset firms have a cost advantage in producing low-quality handsets. These features give rise to the within-market spillover effect from international handset firms to domestic handset firms and the cross-market spillover effect to the wireless service market, and thus to the positive welfare effects for consumers. We use counterfactual simulations to quantify these effects and examine a proposed ban on low-cost handsets by Chinese handset firms.

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A Estimation Details

A.1 Definition of Potential Products

We define potential products for each handset firm as follows.[8] Since each product is a triple of (firm, technology, quality), we define the set of potential products for different firms and 3G vs. 4G technology separately.

An international handset firm's potential 3G products Let $\underline{q_{3G}}$ and $\overline{q_{3G}}$ represent the minimum and maximum qualities across all 3G handsets in the sample. For each international handset firm f and period t prior to 2017Q1, we define its potential 3G products in three steps:

1. Define a vector of grid points between $\underline{q_{3G}} - 1$ and $\overline{q_{3G}} + 1$ with increment 1.

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

3. Define the set of potential 3G products for handset firm f in period t as the union of the remaining points and the qualities of its observed 3G products $\{q_j : j \in \mathcal{J}_{ft}^{(h)}\}$.

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

For periods after 2017Q1, we define this set as empty to be consistent with the data, that is, no international handset firms produced 3G handsets after 2017Q1.

An Indian handset firm's potential 3G products During our sample period, 3G technology was still an evolving technology for Indian handset firms. Therefore, we define their potential 3G products differently than we define the potential 3G products of an International handset firm. First, we allow the highest quality to increase over time. To this end, we replace $\overline{q_{3G}} + 1$ in Step 1 with $\overline{q_{3G}}_t^{Indian} + 1$, the maximum quality of all Indian 3G handsets at time t. Second, this set is not empty in any period, again to be consistent with the data.

An international handset firm's potential 4G products Because 4G technology was new in India during our sample period, we define the potential 4G products differently than we define potential 3G products: even for international handset firms, we use an origin/time-specific maximum to define the vector of quality grid points.

Specifically, for each international handset firm f and period t after 2013Q1 (the first quarter in which 4G handsets were sold in India), we define its potential 4G products in three steps:

1. Define a vector of grid points between $\underline{q_{4G}} - 1$ and $\overline{q_{4G}}_t^{International} + 1$ with increment 1, where $\underline{q_{4G}}$ is the minimum quality among all 4G handsets in the sample and $\overline{q_{4G}}_t^{International}$ is the maximum quality among all international 4G handsets at the time.

2. Remove a point from this vector if the quality of an observed 4G handset of firm f (i.e., q_j for $j \in \mathcal{J}_{ft}^{(h)}$) is within 0.5 of that point.

3. Define the set of 4G potential products for handset firm f in period t as the union of the remaining points and the qualities of its observed 4G products $\{q_j : j \in \mathcal{J}_{ft}^{(h)}\}$.

For periods prior to 2013Q1, we define this set as the potential 4G product set in 2013Q1.

An Indian handset firm's potential 4G products The definition is similar to that for an international handset firm except for two differences. First, $\overline{q_{4G}}_t^{International}$ in Step 1 is replaced by its Indian counterpart, $\overline{q_{4G}}_t^{Indian}$. Second, the cutoff quarter is changed from 2013Q1 to 2015Q2, when the first Indian 4G handset was introduced.

A.2 Details on Solving the Dynamic Network Expansion Game

Computing the equilibrium of the dynamic network expansion game faces 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 empty 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, especially for earlier periods, it is still large.

To deal with this issue of a large state space, we follow Sweeting (2013) to compute the value function at a subset of possible state variable values and approximate the value function at other state variable values 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 each time period t. Let $\hat{\lambda}_{ct}(\theta)$ be the estimated coefficients. We approximate the value function $V_{ct}(\mathcal{R}_t, \theta)$ for each $\mathcal{R}_t$ by the $s_t(\mathcal{R}_t)\hat{\lambda}_{ct}(\theta)$.