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

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April 19, 2024

**Abstract**

This paper studies indirect network effects between two complementary markets and quantifies how the presence of technologically more advanced international firms in one market helps the development of the other market (a cross-market spillover effect), which, in turn, benefits domestic firms in the first market (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

*We thank Neil Shah and Tarun Pathak from Counterpoint Research for sharing the handset data and providing important insights about the market. We thank Jeronimo Callejas for sharing the GSMA Intelligence data with us. We thank the participants at ASU Annual Empirical Microeconomics Conference, Barcelona Summer Forum, CEPR VIO, Cornell, HBS, IIOC, Indiana, Microsoft, MSU, Northwestern, Princeton, Toulouse School of Economics, and Penn for their valuable comments.

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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 operators, 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 operators 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. Jio also sells handset/plan bundles, where the handset 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]

## 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.

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

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.

Third, 4G handset sales increased and 4G network coverage expanded over time. The

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."

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

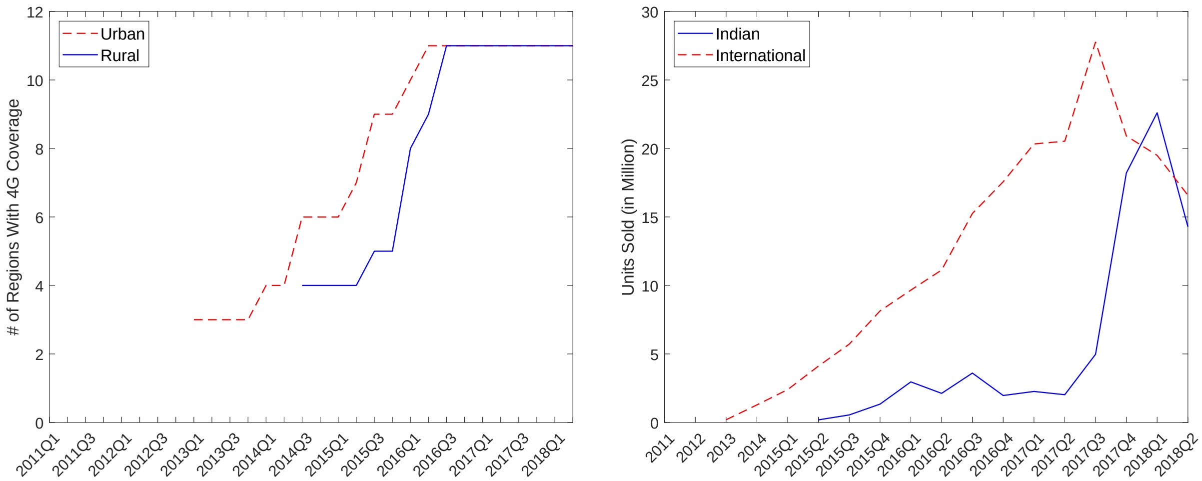
To quantify how the presence of the technological more advanced international firms in the handset market affects the development of the wireless service market (the cross-market spillover effect) and the domestic firms in the handset market (the within-market spillover effect) as well as consumers (the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

[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.

## 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 for 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 Jio handsets (under the brand name of LYF) are not compatible with non-Jio plans.

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

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

where the vector $x_{jkt}$ includes three sets of covariates. First, it includes a quality index of handset $j$ that depends on the observable product characteristics $x_j$ as $q_j = x_j\rho$, where $\rho$ are parameters to be estimated and the first dimension of $\rho$ is normalized to 1. In other words, following Fan and Yang (2020), who also study in the cellphone market, we assume that the consumer utility depends on the 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 $1\{4G_j, 4G_k\}$, which takes value 1 if and only if handset $j$ is a 4G handset and plan $k$ is a 4G plan. With the inclusion of this variable, we allow consumers to gain a differential utility from using a 4G handset on a 4G network above and beyond 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 various levels.

In the utility function (1), $p_{jt}$ is the price for handset $j$ and $p_{kt}$ is the price for 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 each follows a standard normal distribution. We also include the term $\xi^{(h)}_{jt}$ and $\xi^{(p)}_{kt}$ to capture unobservable handset and plan characteristics. Finally, the term $\varepsilon_{ijkt}$ captures consumer idiosyncratic taste and is assumed to be i.i.d. and follows a type-1 extreme value distribution. The utility from the outside option is normalized to be $u_{i0t} = \varepsilon_{i0t}$.

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

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

where $\boldsymbol{p}_{rt} = (p_j + p_k, jk \in \mathcal{J}^{(hp)}_{rt})$ and $\boldsymbol{x}_{rt} = (x_{jkt}, jk \in \mathcal{J}^{(hp)}_{rt})$. Similarly, $\boldsymbol{\xi}_{rt}$ is the collection of $(\xi^{(h)}_{jt}, \xi^{(p)}_{kt})$ for handsets compatible with at least one plan in $\mathcal{J}^{(p)}_{rt}$ and plans in $\mathcal{J}^{(p)}_{rt}$. Finally, $G_r(\alpha_{it})$ is the distribution function of $\alpha_{it}$) in region $r$.

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

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

[3] The price for 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 and 16.43 months from 2018 on, 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 as $(\boldsymbol{p}_{rt}, \boldsymbol{x}_{rt}, \boldsymbol{\xi}_{rt})$ for all handsets and plans in the nation instead of those in a region, and $s_{jkrt}$ is set to be 0 for handset and plan combinations $jk$ that are not compatible. 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 that a carrier has not established its 4G network, the carrier chooses a subset of these regions to expand its 4G network into. An empty subset indicates no expansion in this 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, where handset firms choose the set of handsets to sell given the network structure in the country. Intuitively, the larger the 4G network coverage, the larger the profits handset firms get from selling 4G phones. Conversely, the more 4G phones that are anticipated 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 such interdependence between the handset market and the network service market. In our model, handset firms and carriers also decide on the prices of handsets and network plans.

We model handset firms' product choice as a static problem. Solving a dynamic game with two sets of interdependent firms and each makes a discrete decision with a large choice set (carriers choose a subset of regions to expand 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 developed for the global market or below the technology frontier during our sample period. As a result, selling these phones is unlikely to involve a large sunk cost 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 are sold. Anticipating this, carriers have higher incentives to develop their 4G networks compared to a scenario without the international handset firms.

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

Over time, any change in the handset market leading to increases in 4G phone sales (e.g., decreased marginal cost over time) gives carriers incentives to expand their 4G network further. Eventually, given a larger 4G network coverage, even Indian handset 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 expansions.

### 3.2.1 Static Game of Product Choice and Prices

The static game consists of two stages where handset firms choose products in the first stage and both handset firms and carriers choose prices in the second stage. We describe these two stages backward.

At the pricing stage, handset firms and carriers observe the set of handsets and plans available as well as the demand and marginal cost shocks for each handset and each plan. 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 costs as

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

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

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: $c_{kt}^{(p)} = Plan_k + \omega_{kt}^{(p)}$.

One exception to the profit-maximization problems in (5) and (7) is Jio's problem. Jio sells a network plan (i.e., Jio 4G service) as well as a set of 4G handsets under the brand name LYF. Therefore, Jio's problem is to choose both the plan price and the prices of the

LYF handsets to maximize the total profit coming from both handset sales and plan sales:

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

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 handset $\mathcal{H}_{ft}$ 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 cost associated with offering a specific 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 handset firm $f$'s profit in (5), take the expectation over the demand and marginal cost shocks $(\boldsymbol{\xi}_t,\boldsymbol{\omega}_t)$, and multiple it 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 $\pi_{ft}^{(handset)}(\{\mathcal{J}_{ft}^{(h)}\}_{f=1}^{F},\{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R})$.

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 $C_{jt}$ be the fixed cost of offering handset $j$. In (9), we write firm $f$'s expected variable profit as $\pi_{ft}^{(handset)}(\mathcal{J}_{ft}^{(h)},\mathcal{J}_{-ft}^{(h)},\{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R})$, where $\mathcal{J}_{-ft}^{(h)}$ represents the set of handsets offered by handset firm $f$'s competitors, to highlight that handset firm $f$ chooses its product portfolio $\mathcal{J}_{ft}^{(h)}$.

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, $\pi_{ft}^{(handset)}(\{\mathcal{J}_{ft}^{(h)}\}_{f=1}^{F}, \{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R})$. In (10), we plug in the equilibrium handset portfolios $\{\mathcal{J}_{ft}^{(h)*}(\{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R})\}_{f=1}^{F}$ and obtain a function of $\{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R}$. This profit function $\Pi_{ct}(\{\mathcal{J}_{rt}^{(p)}\}_{r=1}^{R})$ 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, the 4G technology was the new technology and 4G networks expanded in India. Correspondingly, we study carriers' 4G network expansion decisions and treat the 2G and 3G networks as exogenous in our model.

We focus on the four largest carriers and treat the other four fringe carriers' networks as exogenous. These four carriers are Airtel, Vodafone, Idea, and Jio, which are sorted according to their total subscribers during our sample period. They account for 95% of the 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 non-stationarity 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 in almost all regions studied in the paper.[6]

We first introduce some notations 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 the period profit of a carrier 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 equation (10). Since the 2G and 3G networks are treated as exogenous and whether carrier $c$ provides 4G services in region $r$ determines whether the 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.

Formally, when it is a carrier's turn to move, this carrier's action $a_{ct}$ is to choose a subset from the regions that it has not entered with 4G services (denoted by $\mathcal{R}\backslash\mathcal{R}_{ct}$). For Jio, however, in line with the observed data, we assume that its decision is either entering into

[5]The other four firms either only offered 2G and 3G services or had very limited 4G services. Specifically, during our sample period, BSNL and MTNL only offered 2G and 3G services, and did not have the rights to offer 4G networks in any regions. Aircel mostly operated 2G and 3G networks and offered limited 4G services before exiting the market in 2018Q2. Similarly, Reliance Communication also mostly operated offering 2G and 3G services, and declared bankruptcy in 2019.

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

all regions altogether 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 is not expanding in this period. Otherwise, this carrier pays the entry cost $f_c(a_{ct}, \theta)$ and its 4G network becomes $\mathcal{R}_{ct} \cup a_{ct}$ 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.

When it is carrier $c$'s turn to move, carrier $c$ observes the network structure $\mathcal{R}_t = (\mathcal{R}_{1t}, ..., \mathcal{R}_{4t})$ and its own shocks $\varepsilon_{ct} = (\varepsilon_{ct}(a_{ct}), a_{ct} \in \mathcal{A}_c(\mathcal{R}_{ct}))$. It knows that carriers $c' < c$ have decided but do not observe their shocks $\varepsilon_{c't}$ or their actions $a_{ct'}$. Next period, the network structure becomes $\mathcal{R}_{t+1}$ where $\mathcal{R}_{ct+1} = \mathcal{R}_{ct} \cup a_{ct}$. Let $V_{ct}(\mathcal{R}_t, \varepsilon_{ct})$ be the value function of carrier $c$ at time $t$ and $\delta$ 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 type-1 Extreme Value distribution with location parameter 0 and scale parameter $\phi$. Under this assumption, the Bellman equation becomes

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

where $\gamma$ 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 $\{\Pr_{ct}(a_{ct}|\mathcal{R}_t),\ a_{ct} \in \mathcal{A}_c(\mathcal{R}_{ct}),\ c,\ t\}$ 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) for any $c, t$, $\mathcal{R}_t$ when 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 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 instrument variables following Berry, Levinsohn, and Pakes (1995) and the differentiation instrument variables following 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 in, for example, 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 variations across handset technology fixed effects, plan technology fixed effects, handset firms, carriers, and time. Therefore, though imperfect, it seems reasonable to assume that the transitory shock specific to a handset or a plan is unknown to firms when they make their product choices. To construct the supply-side moments, we first back out marginal costs based on first-order conditions with respect to prices and then interact the unobservable marginal cost shocks with the marginal cost covariates. Appendix A provides more details about the estimation.

Table 3 reports the demand estimation results. The estimates indicate that consumers dislike paying a high price and that price sensitivity decreases with income. At the average income of 101,495 INR, the average price coefficient is -10.13. The standard deviation of the unobservable heterogeneity in price sensitivity is about 1/5 of the average price coefficient. We also find that consumers prefer handsets with larger screens, more storage, and more RAM. For example, increasing the storage from 64GB to 128GB is equivalent to a decrease in price by around 66K INR on average, which about half of the average price for a 4G handset. The effects of camera resolution and battery capacity on utility are also positive though statistically insignificant.

Consumers also gain more utilities from using a 4G phone on a 4G network. The estimated coefficient of 4.0 is tantamount to a willingness to pay of 3959 rupees given the average price coefficient. Consumer 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 not surprising because consumers only enjoy the advanced feature of a 4G phone with 4G network and have to have a 4G phone to enjoy the

Table 3: Estimation Results: Demand

| | Est. | Std. Error |
|---|---|---|
| Price (10K INR) | -13.2*** | 2.3 |
| Price × Income | 1.5*** | 0.6 |
| Price × Normal Draw | 1.3*** | 0.4 |
| Screen Size (Inch) | 0.3*** | 0.1 |
| Camera (MP) | 0.03 | 0.02 |
| Storage (10GB) | 0.7*** | 0.1 |
| RAM (GB) | 0.3* | 0.2 |
| Battery Capacity | 0.2 | 0.1 |
| $\mathbb{1}$(4G Handset)× $\mathbb{1}$(4G Network) | 4.6*** | 0.8 |
| 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 $\beta_q$ is the coefficient of quality in the utility function and $\rho_l$ is the weight of the $l^{th}$ characteristic in the quality index.

fast speed of a 4G network. The complementarity between 4G handsets and 4G networks gives rise to the interdependence between handset firms' behaviors and carriers' decisions on the 4G network rollout, which is the foundation for the spillover effects we study.

Table 4 reports the estimated handset marginal cost parameters. 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 for producing low-quality handset is smaller for Indian firms than for international firms ($\hat{\gamma}_1 < 0$). In other words, Indian firms have a cost advantage at producing low-quality handsets, but their marginal costs increase at a faster speed 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 when the 4G network coverage is large enough later in Indian's 4G rollout.

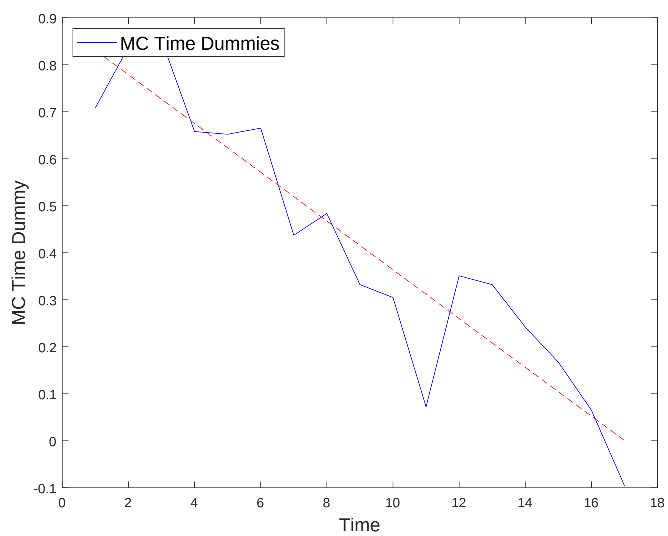
We also find a downward trend in marginal costs. Figure 2 shows the estimated time fixed effects where the last quarter is used as a baseline. Such a downward trend in the marginal cost of producing a 4G handset supports a continuous expansion of the 4G network. This

Table 4: Estimation Results: Handset Marginal Cost

| | Est. | Std. Error |
|---|---|---|
| $\mathbb{1}$(Indian) ($\gamma_1$) | -1.3*** | 0.2 |
| Quality ($\tau_0$) | 0.1*** | 0.02 |
| Quality×$\mathbb{1}$(Indian) ($\tau_1$) | 0.1* | 0.6 |
| Time FE | Yes | |
| Jio First Year FE | Yes | |

is because declined marginal costs may lead to lower prices and more product variety for 4G handsets, increasing the attractiveness of 4G handset options for consumers. Given the estimated consumer taste for the combination of a 4G handset on a 4G network, consumers are also more likely to buy a 4G network plan when available. Given all these, carriers have incentives to expand their 4G network over time as marginal costs of producing 4G handsets decline over time.

Figure 2: Estimated Time Fixed Effects in Log(Marginal Cost)




Notes: This graph plots the estimated fixed effects in the logarithm of marginal cost. The last quarter of the sample (2018Q2) is the baseline.

## 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 in the market, their fixed costs should be bounded from above and conversely, the fixed cost of a not-offered product is 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.

We define potential products for each handset firm as follows.[7] Each product is a triple: its firm, technology, and quality. The quality index of a handset in the data varies between 0.3 and 24.6. To define potential 3G handsets, we find the minimum and the maxmimum qualities across all 3G handsets in the sample (denoted by $\underline{q_{3G}}$ and $\overline{q_{3G}}$). For each international handsest firm $f$, we define a vector starting from $\underline{q_{3G}} - 1$, increasing with an increment of 1, and capped at $\overline{q_{3G}} + 1$. We remove a quality value from this vector if firm $f$ has a product whose quality is different from this quality value by less than 0.5. We then define the set of 3G potential products for handset firm $f$ as the union of its observed products $\{q_j : j \in \mathcal{J}_{ft}^{(h)}\}$ and this vector. We restrict this set to be empty for quarters after 2017Q1 to be consistent with the data,i.e., no international handset firms produced 3G handsets after 2017Q1. For Indian handset firms, given that 3G was still a developing technology during our sample, we define their 3G potential products differently. First, the cap of the quality

[7] We treat Apple and LYF's product portolios as exogenous and thus do not need to define their potential products. Apple does not produce handsets specific to India. Its product portfolio is largely driven by the global market. As for LYF handsets, Jio did not introduce the LYF handsets when they established their 4G network largely for exogenous reasons.

vector varies over time. Specifically, we find the maximum quality for all Indian 3G handsets at time $t$ and use $\overline{q_{3G}}_t^{Indian}+1$,as the cap for the vector at the time. Second, we do not define an empty set for any time period, again to be consistent with the data.

Because the 4G technology is new in India during our sample, we define the potential 4G products differently from how we define potential 3G products. First, even for international handset firms, we use an origin/time-specific maximum to construct the quality cap. Second, for an international handset firm, we define its 4G potential products before 2013Q1 as its 4G potential products in 2013Q1, the first quarter when 4G handsets were sold in India. For an Indian handset firm, the relevant cutoff quarter is 2015Q2, when the first 4G Indian handset was introduced.

Table 5 reports estimated fixed costs by origin and quality segment. For the purpose 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 groups the handsets into three bins according to their qualities. As mentioned, the quality of a handset varies between 0.3 and 24.6 in the sample. The highest quality among Indian handset is, however, 10.4. Therefore, we consider three bins: (0,6], (6, 11], (11, 25]. In each quality segment, we report the median fixed cost across 4G handsets of a given origin (Indian, other-Asian, and non-Asian). From the table, we can see that other Asian handset firms enjoy substantial advantages in terms of the fixed cost of selling a 4G handset compared to their Indian competitors, for both low-quality and medium-quality handsets. As for the high-quality segment, only the international handset firms are present.

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

| | Median Fixed Cost (Million INR) | | |
|---|---|---|---|
| Origin | Low-Quality | Medium-Quality | High-Quality |
| Indian | 583 | 679 | - |
| Other Asian | 103 | 346 | 915 |
| Non-Asian | 15 | 19 | 231 |

Notes: This table shows the median estimated fixed cost of handsets by origin of the handset firm and quality segment.

The finding that international handset firms incur lower costs for selling 4G handsets implies that they are more likely to sell 4G handsets even with a relatively small 4G network coverage, providing incentives for carriers to develop their 4G networks. This is the base for the cross-market spillover effect, leading to faster 4G rollout in both markets and benefiting consumers.

## 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 while capturing the key economic patterns.[8] 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.

To ease the computational burden, we also restrict each firm's action space as follows. First, we assume that carriers choose to establish their 4G networks in Metro regions, which are more developed and richer, before expanding to other region categories. Second, we assume that a carrier will expand into Category-A or Category-B regions only after every Metro region has at least one carrier. Similarly, a carrier will expand into Category-B regions only after every Metro region and every Category-A region have at least one carrier. Third, a carrier enters no more than two Metro regions simultaneously, no more than three Category-A regions simultaneously, and no more than three Category-B regions simultaneously. All three assumptions are consistent with the observed data.

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 $\theta_c$ 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 ($\phi$). Let $\theta = (\theta_1, ..., \theta_4, \phi)$.

We estimate $\theta$ 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.

To compute the equilibrium of the dynamic network expansion game, we first 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 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 $\theta$ to maximize the likelihood function. Then, for each trial of the entry cost parameters $\theta$, we solve for the equilibrium of the dynamic network expansion game $Pr_{ct}(a_{ct}|\mathcal{R}_t, \theta)$ using backward

[8] These 12 regions 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).

induction. We follow a strategy similar to that in Sweeting (2013) to deal with the large state space issue. See Appendix A 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 welfare effects on 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 alters the pricing competition in both the handset and the network markets. Moreover, it affects the set of handsets in the market directly because the handsets produced by these international handset firms disappear with the removal of these firms. It also affects product availability indirectly by affecting domestic handset firms' product choices. Finally, their absence influences the 4G network expansions in the wireless service market, which, in turn, affects Indian handset firms' product choices and the pricing competition in these two markets. Our model allows for all these effects. Our simulation, therefore, captures all these effects.

In the second counterfactual simulation, we make all international handset firms domestic. Compared to the first counterfactual simulation where 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 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 averaged across handsets by domestic firms to the average fixed cost averaged across 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 handset firm. The Indian government is currently considering banning low-cost Chinese handsets priced below INR 12,000 in order to push major Chinese handset firms from the lower end of its handset market.

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 phones and the estimated complementarity between 4G phones and 4G handsets, we expect a slower expansion of 4G network coverage in the counterfactual scenario.

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

In terms of welfare, both the slower expansion of 4G network coverage and the slower development of the 4G phone market reduce consumer surplus. Due to the complementarity between the two markets, carriers are expected to earn less profit with the absence of international handset firms. As for domestic handset firms' profits, 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. When the latter is large enough, we expect their profits to decline.

# 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 benefits 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 establish 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 decreases 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.

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# A Estimation Details

## Back Out Marginal Cost

We back out the marginal costs based on the first-order conditions. Specifically, the first-order condition with respect to handset price $p_{jt}$ (corresponding to the handset firm's profit-maximization problem in (5)) is

$$s_{jt}^{(h)} + \sum_{j' \in \mathcal{J}_{ft}^{(h)}} \frac{\partial s_{j't}^{(h)}}{\partial p_{jt}} (p_{j't} - c_{j't}^{(h)}) = 0, \tag{A.1}$$

which allows us to back out the handset marginal cost $c_{jt}^{(h)}$.

Similarly, the first-order condition with respect to plan price $p_{kt}$ (corresponding to the carrier profit-maximization problem in (7)) is

$$s_{kt}^{(p)} + \sum_{k' \in \mathcal{J}_{ct}^{(p)}} \frac{\partial s_{k't}^{(p)}}{\partial p_{kt}} (p_{k't} - c_{k't}^{(p)}) = 0, \tag{A.2}$$

which allows to obtain the plan marginal cost $c_{kt}^{(p)}$.

The first-order conditions corresponding to Jio's problem in (8) are

$$\begin{aligned} s_{kt}^{(p)} + \frac{\partial s_{kt}^{(p)}}{\partial p_{kt}} (p_{kt} - c_{kt}^{(p)}) + \sum_{j \in \mathcal{J}_{ft}^{(h)}} \frac{\partial s_{jt}^{(h)}}{\partial q_{kt}} (p_{jt} - c_{jt}^{(h)}) = 0, \\ \frac{\partial s_{kt}^{(p)}}{\partial p_{jt}} (p_{kt} - c_{kt}^{(p)}) + s_{jt}^{(h)} + \sum_{j' \in \mathcal{J}_{ft}^{(h)}} \frac{\partial s_{j't}^{(h)}}{\partial p_{jt}} (p_{j't} - c_{j't}^{(h)}) = 0. \end{aligned} \tag{A.3}$$

One exception is the marginal costs for the Jio's handsets in the year when they were launched. Jio launched its handsets as promotional products under the brand name LYF in the first year. In order to accommodate the low promotional prices offered by Jio in the first year, we model Jio's pricing strategy in its first year as a 5% markup rule for its LYF handsets.

## Estimate the Dynamic Network Expansion Game

We estimate the parameters in the dynamic network expansion game using the maximum likelihood approach that requires solving for the equilibrium for each trial or parameters. Recall that the parameters are $\theta = (\theta_1, \theta_2, \theta_3, \theta_4, \phi)$.

Computing the equilibrium of the dynamic network expansion game faces the challenge of a large state space. The state variables are $\mathcal{R}_t = (\mathcal{R}_{1t}, ..., \mathcal{R}_{4t})$, where $\mathcal{R}_{ct}$ is a subset of 12 regions. Given that there are $2^{12}$ such subsets, there are $(2^{12})^3 \times 2$ possible values for $\mathcal{R}_t$.[9]

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

To provide more details, we now explain our algorithm for computing the equilibrium $\Pr_{ct}(a_{ct}|\mathcal{R}_t, \theta)$ using backward induction step by step.

The following calculations are independent of the parameters $\theta$:

- For each drawn state $d$, carrier $c$, and period $t$, we compute $\Pi_{ct}(\mathcal{R}_t^d)$. We do so by solving for the product-choice equilibrium following the algorithm in Fan and Yang (2020).
- For each drawn state $d$, carrier $c$, any $(a_{1T}, ..., a_{4T})$ such that $a_{cT} \in \mathcal{A}_c(\mathcal{R}_{cT}^d)$, we compute $V_{cT+1}(\mathcal{R}_{1T}^d \cup a_{1T}, ..., \mathcal{R}_{4T}^d \cup a_{4T})$ according to (13).

The following calculations are done for each trial of parameters $\theta$. We loop over $t = T, T-1, ..., 1$ backwards. For each period $t$, we take the following steps:

(a) Unless $t = T$, for each state $d$, any $(a_{1t}, a_{2t}, a_{3t}, a_{4t})$ such that $a_{ct} \in \mathcal{A}_c(\mathcal{R}_{ct}^d)$, and any carrier $c$, we compute $V_{ct+1}(\mathcal{R}_{1t}^d \cup a_{1t}, ..., \mathcal{R}_{4t}^d \cup a_{4t}, \theta)$ as a linear function of the reduced state variables: $s_{t+1}(\mathcal{R}_{1t}^d \cup a_{1t}, ..., \mathcal{R}_{4t}^d \cup a_{4t})\hat{\lambda}_{ct+1}(\theta)$. The coefficient $\hat{\lambda}_{ct+1}(\theta)$ has been obtained in step (c) in the previous iteration for $t+1$. For $t = T$, $V_{cT+1}(\mathcal{R}_{1T}^d \cup a_{1T}, ..., \mathcal{R}_{4T}^d \cup a_{4T})$ is computed above.

[9] Note that this number is not $(2^{12})^4$ because Jio's decision is either entering into all 12 regions altogether or not at all. Also note that the restrictions on the action space explained in Section 4.3 reduce the state space, especially for earlier periods. However, the state space is still large.

(b) For any state $d$, we compute the equilibrium choice probabilities $Pr_{ct}(a_{ct}|\mathcal{R}_t^d, \theta)$ for any $a_{ct} \in \mathcal{A}_c(\mathcal{R}_{ct}^d)$, denoted by $\vec{Pr}_{ct}$, using the following iterative process:

(b.1) We start with a guess of $\vec{Pr}_{ct}$, denoted by $\vec{Pr}_{ct}^0$, for $c = 1, 2, 3$.

(b.2) In iteration $h$, we start with the last mover, carrier 4, and compute its choice probabilities, $\vec{Pr}_{4t}^h$, as:

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

where the expectation is taken based on $V_{ct+1}(\mathcal{R}_{1t}^d \cup a_{1t}, ..., \mathcal{R}_{4t}^d \cup a_{4t}, \theta)$ computed in (a) and the probability vectors $\vec{Pr}_{ct}^{h-1}$ for $c = 1, 2, 3$.

(b.3) For carrier 3, the computation of $\vec{Pr}_{3t}^h$ is based on $\vec{Pr}_{4t}^h$ computed in step (b.2) and $\vec{Pr}_{ct}^{h-1}$ for $c = 1, 2$.

(b.4) For carrier 2, the computation of $\vec{Pr}_{2t}^h$ is based on $\vec{Pr}_{ct}^h$ for $c = 3, 4$ steps (b.2)–(b.3) and $\vec{Pr}_{ct}^{h-1}$ for $c = 1$.

(b.5) For carrier 1, the computation of $\vec{Pr}_{1t}^h$ is based on $\vec{Pr}_{ct}^h$ for $c = 2, 3, 4$ computed in steps (b.2)–(b.4).

(b.6) We repeat the steps (b.2)–(b.5) until we reach a fixed point, i.e., when the two vectors $(\vec{Pr}_{ct}^h, c = 1, 2, 3, 4)$ and $(\vec{Pr}_{ct}^{h-1}, c = 1, 2, 3, 4)$ are very close.

(c) Based on the equilibrium probabilities obtained in step (b), we compute the value function $V_{ct}(\mathcal{R}_t^d, \theta)$ for any state $d$ and regress $V_{ct}(\mathcal{R}_t^d, \theta)$ on $s_t(\mathcal{R}_t^d)$ to obtain $\hat{\lambda}_{ct}(\theta)$ for $c = 1, 2, 3, 4$.

To construct the likelihood function, we need to evaluate $\Pr_{ct}(a_{ct}|\mathcal{R}_t, \theta)$ at the data point, which has been computed in the procedure above (step (b)) because the data points $\mathcal{R}_t$ are included in the drawn states $\mathcal{R}_t^d$.