Does Vertical Integration Increase Innovation?

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Abstract

This paper studies the effects of vertical integration on innovation in the chipset and smartphone industry. I formulate and estimate a dynamic structural model of the upstream chipset maker Qualcomm and downstream smartphone handset makers. The two sides make dynamic investment decisions and negotiate chipset prices via Nash bargaining. Using the estimates, I simulate market outcomes should Qualcomm merge with a downstream handset maker. I find that the vertical merger would significantly increase innovation rates and social welfare, driven primarily by the investment coordination of the two merged firms. I also explore the roles of upstream product availability, downstream product substitution and consumer price sensitivity.

1 Introduction

In vertical industries, upstream and downstream innovations are often complementary. Upstream firms upgrade the core technologies essential to enhance performance, and downstream firms combine the new technology with new designs in the next generation of consumer products. There are many examples, such as traction batteries (upstream) and electric vehicles (downstream) and CPU's (upstream) and personal computers (downstream). Given the prevalence of vertical structures, this paper studies the effects of vertical integration on pricing, innovation and welfare.

There is a large theoretical literature on vertical integration.[1] Theory suggests that vertical integration may affect both investment and price decisions. Vertical integration may be pro-investment by aligning the investment incentives of the merged firms. Firms also set prices differently when an upstream firm is merged with a downstream firm, producing the well known efficiency trade-off

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[1]Examples of surveys include Perry (1989), Holmström and Roberts (1998), Tirole (1999), Riordan (2008) and Aghion and Holden (2011). The list is far from exhaustive.

between two pricing forces: on one hand, double marginalization is reduced within the integrated firm so charge consumers face lower prices; on the other hand, the integrated firm has an incentive to charge higher prices to downstream rivals (raising rivals' cost or the foreclosure effect). However, predictions of the net effects on firm profits depend on the nature of downstream product competition and how firms set prices,[2] and because investment is driven by the marginal value of investment, i.e. a firm's post-investment profit less the pre-investment profit, it is unclear how the price effects of vertical integration affect investment.

Understanding the relative magnitudes and the interaction of the investment coordination effects and price effects of vertical integration is crucial for policy and regulation. For example, the potential tradeoff between one firm's innovation and industry-wide innovation was a key issue in the European antitrust case against Microsoft in 2004. Microsoft owned the popular proprietary operating system used on computer servers and foreclosed other server software companies. Microsoft argued in its defense that the foreclosure would increase its own innovation. The European Commission, however, believed that if Microsoft were to provide downstream rivals (server software producers) with reasonable access to its upstream technology (operating system), "the positive impact on the level of innovation in the whole industry outweighed the negative impact of the dominant undertaking's incentives to innovate".[3] The court ruled against Microsoft. In effect, the authorities believed that preventing foreclosure would increase the innovation of other downstream firms, and the resulting benefits would be greater than the potential reduction in the integrated firm's innovation.

In this paper, I use an empirical model of pricing and dynamic investment to study the investment coordination and price effects of vertical integration in the context of the chipset and smartphone industries. The main novelty is the specification of both dynamic upstream and downstream firms. The upstream industry consists of a dominant firm ("Qualcomm") and a fringe, and the downstream firms are a finite number of handset makers. Qualcomm invests to increase the quality of its chipsets. Similarly, downstream handset makers invest to increase the quality of their handsets, but some handset makers are constrained by Qualcomm's chipset quality. Handset makers also choose the proportion of handsets that use Qualcomm chipsets. A handset maker's sunk cost of innovation depends on the amount of its quality increase and the proportion of its handsets using Qualcomm chipsets. The dynamic game of innovation determines the set of products in every period. Conditional on the set of products, Qualcomm and handset makers first negotiate chipset prices via Nash bargaining. Handset makers then take the chipset prices as given, set retail prices and sell to the consumers. Period profits are determined by the subgame perfect equilibrium of the overall static pricing game. When deciding whether to innovate, upstream and downstream firms weigh the gains in the present discounted values of future profits due to innovation against the sunk costs, and the dynamic decisions form a Perfect Bayesian Equilibrium.

The model is estimated using data from the US smartphone market from 2009 to 2013. The

[2]Predictions can be more definitive in some more special cases, such as Riordan (1998).

[3]Case T-201/04, Microsoft Corp. v. Commission, 2007 E.C.R. II-3825 (Ct. First Instance).

estimation procedure has three steps. First, price and quantity data of handsets allow me to estimate a static random coefficient logit model of consumer demand for smartphones. I refer to a linear combination of product characteristics, where the weights are given by the estimated demand coefficients, as the quality index of the products,[4] and I use this index to construct the quality frontiers of Qualcomm and handset makers. Next, I recover chipset prices and other marginal costs of smartphones using data on chipset markups and equilibrium pricing conditions. The first two steps do not involve estimating the dynamic model. The estimates and the pricing equilibrium assumption imply period profit functions of upstream and downstream firms. In the last step, I use the estimated period profit functions and the evolution of quality frontiers of Qualcomm and handset makers to estimate the cost function of innovation. To keep the computation tractable, I estimate a dynamic game among the upstream Qualcomm and three handset makers: Apple, Samsung and HTC, the top three handset makers by revenue. The three handset makers account for 70.2% of the total revenue during the sample period. Consistent with data, I assume that Apple only uses its own chipsets, while HTC only uses Qualcomm chipsets. Samsung can adjust the proportion of its handsets using Qualcomm chipsets. Samsung and HTC are constrained by Qualcomm chipset quality, while Apple is not (it can innovate to a quality level not yet reached by Qualcomm). I use the method of simulated moments to estimate the model. The dynamic model is solved for every trial of parameters. To ensure the existence and uniqueness of the dynamic equilibrium, I make two assumptions: 1) the dynamic game has a finite horizon, and 2) firms make investment decisions sequentially within every period.[5]

I examine the counterfactual should Qualcomm merge with HTC, a key handset maker that primarily uses Qualcomm chipsets. Using the model, I simulate the net effects of vertical integration and decompose the net effects into the investment coordination effects and price effects. In the main specification, I find that upstream innovation, defined as the average increase of quality per period, increases by 38%, and the innovation rate of the integrated handset maker increases by 23%. The increase primarily comes from the investment coordination of Qualcomm and HTC: the integrated firm internalizes the marginal value of HTC innovation for Qualcomm and the marginal value of Qualcomm innovation for HTC. The price effects also increase the integrated firm's innovation, but are much smaller than the investment coordination effects. Moreover, Samsung is less often constrained by the upstream innovation, and Samsung innovation increases by 26%, while Apple innovation increases by 21%. Primarily due to the increase in innovation, consumer surplus increases by about 18%. In addition, while the raising rivals' cost effect increases Samsung's retail prices, the elimination of double marginalization lowers HTC prices, and the overall price effects increase the consumer surplus. The total surplus (consumer surplus and variable profits) increases by over 12%. The findings thus suggest that vertical integration policies should fully take into account a vertical merger's dynamic implications and in particular the effects of investment coordination, which may be much larger than the price effects.

[4]The demand model is the same as Fan and Yang (2016)

[5]The related robustness checks are discussed in Appendix D.

Contributions and Related Literature This paper's dynamic model of innovation is grounded in the theory of incomplete contracts. Specifically, I assume that vertically separated firms cannot contract on the amount of investment prior to the realization of investment. The assumption rules out the possibility that vertically separated firms can sign a "cooperative" contract, where one side agrees to make investment in exchange for a future transfer. The investment coordination effect studied in the counterfactual exercise quantifies the efficiency gains of allowing Qualcomm and HTC to overcome the non-contractibility of investment. Lafontaine and Slade (2007) surveys the empirical literature on vertical integration. Examples of empirical work that examines the competitive effects of vertical integration using reduced form analyses includes Waterman and Weiss (1996), Chipty (2001), Hastings (2004), Hastings and Gilbert (2005), Chen and Waterman (2007) and Hortacsu and Syverson (2007), to name a few. Static structural models have also been used to understand the effects of vertical integration in, for example, Brenkers and Verboven (2006), Murry (2015), Asker (2015) and Crawford, Lee, Whinston and Yurukoglu (2015). The model in this paper endogenizes both forward-looking dynamic investment decisions as well as the pricing of intermediate goods. I also contribute to the literature that analyzes innovation with dynamic oligopoly models (Ericson and Pakes (1995), Goettler and Gordon (2011), Borkovsky (2012), Igami (2015) and others) by modeling the complementarity of innovations between the upstream and downstream firms. The static model of product competition is built on the empirical bilateral bargaining framework developed in Horn and Wolinsky (1988). This type of models has been widely used to analyze the pricing of services and physical goods in vertical industries. Examples include Draganska, Klapper and Villas-Boas (2010), Crawford and Yurukoglu (2012), Grennan (2013), Gowrisankaran, Nevo and Town (2014), Crawford et al. (2015) and Ho and Lee (2016), among others. Like many papers in this literature, I assume that firms in my model use linear price contracts. Another strand of the empirical structural literature on vertical relations studies the pricing and welfare effects of alternative upstream-downstream relationships (examples include Sudhir (2001), Villas-Boas (2007), Mortimer (2008) and Bonnet and Dubois (2010)).

Closely related to this paper, Crawford et al. (2015) studies how vertical integration affects program carriage choices, prices and ultimately welfare in the US television market using a multi-stage static model. I focus on the dynamic process of innovation, where firms have rational expectations about the future evolution of the industry. An interesting feature of the model in this paper is that the states and actions of the upstream firm (Qualcomm's quality level and its investment to increase the quality) do not directly affect the current period profit of itself or downstream firms, and Qualcomm is solely motivated to innovate by the expectation that downstream firms will innovate and adopt Qualcomm chipsets in the future. In addition, dynamics may be important when firms are asymmetric (some are integrated and some are not), as Athey and Schmutzler (2001) suggests that firms with initial high quality or low costs may extend their advantage through investment.

Lastly, I examine how different definitions of the disagreement point in the bargaining game may affect counterfactual predictions. Many structural empirical studies assume that products whose prices are negotiated would be dropped at the point of disagreement. I also consider alternative definitions, where a downstream firm switches to an alternative upstream product if the negotiation breaks down. I find that, while the main conclusions are robust, the bargaining model where handset makers drop products at the point of disagreement predicts larger price changes in the counterfactual scenario of vertical integration, even when different bargaining models are estimated on the same data set. The exercise suggests that researchers should conduct robustness checks regarding the definitions of the disagreement point, when there is no additional institutional knowledge to support the use of a particular model.

Road Map In the rest of the paper, I first describe the institutional setting and data in Section 2. Next, I detail the dynamic model of innovation in Section 3 and the static model of bargaining and pricing in Section 4. Section 5 discusses the estimation of the model, and Section 6 reports the counterfactual experiments.

2 Industry and Data

The key upstream firm in this industry, Qualcomm, produces application chipsets.[6] This chipset is the CPU of a smartphone, but it may also combine the functions of a GPU, modem and other components (Yang et al. (2014)). The price of a chipset is usually between \$16 to \$40 (Woyke (2014)). According to reports published by iHS, a tear-down company that tracks component prices, the chipset accounts for 10 to 20% of the material cost of a smartphone.[7]

Qualcomm is the most important company in the upstream chipset industry. In 2009, 53% of non-Apple smartphones sold in the US carried a Qualcomm chipset, and the figure increased to 72% in the first quarter of 2013. Although Qualcomm is able to capture the lion's share of the chipset market, there is no lack of competition. iPhone 4s and later models use Apple's own A series chipsets. Samsung uses its Exynos series chipsets on some of its handsets. There are also a large number of independent chipset makers, such as MediaTek (Taiwan), Texas Instruments (US) and NVIDIA (US). Compared with its competition, one of Qualcomm's advantages is its ability to combine many components (including the modem, GPS, GPU and others) onto a single chipset. By using Qualcomm chipsets, handset makers may save the development cost and the cost of procuring and combining other components. In addition, an integrated chipset saves energy and thus extends battery life, and the more compact design may also save space and allow handset makers to install additional components and add functionality. Much like the role of CPU for personal computers, chipsets are central to the performance of smartphones, because many of the metrics that consumers value, such as processing power (CPU), support of fast network (modem), graphic processing (GPU) and energy efficiency, are determined by the chipset. The innovations of chipsets center on improving all components within the processor without sacrificing too much

[6] Sometime a smartphone modem is also called a communication chipset. Throughout this paper a chipset always means the application chipset.

[7] iHS publishes the marginal cost estimates of select handsets through its press releases. I have collected some of the published data, which are available upon request.

Table 1: Chipset Origin, % of Handset Maker Retail Revenues, 2009 to 1st Quarter 2013

	Qualcomm	Samsung	TI	NVIDIA	Other
Samsung	33.93	62.52	2.68	0.47	0.40
HTC	99.60	0.00	0.21	0.10	0.09
Motorola	14.73	0.00	74.18	8.70	2.39
LG	94.10	0.00	5.05	0.85	0.00
BlackBerry	51.10	0.00	0.00	0.00	48.90

energy efficiency or significantly increasing manufacturing costs (Yeap (2013)).

Qualcomm products are categorized in multiple generations released over time. Snapdragon S1, the first generation of chipsets observed in the data, was released in October 2008. Generation S2, S3 and S4 are released in April 2010, October 2010 and January 2012. S4 is the last generation observed in the data. A later generation typically features significant gains in performance (more cores and higher frequency) and energy efficiency. Following Qualcomm's release of a new generation, its competitors release comparable products. Table 1 reports the origins of chipsets used in major non-Apple handset makers.

The downstream smartphone industry is relatively concentrated. From 2009 to 2012, the top three handset makers were Apple, Samsung and HTC as measured by retail sales revenues, and they accounted for 70% of the US market. Most smartphones in the US are sold through the four major national wireless carriers, AT&T, Verizon, T-Mobile and Sprint. Over time, handset makers adopt new chipsets in new phones and provide many additional improvements, such as larger and clearer screens, longer talk time, and higher definition cameras. Handset makers spend billions of dollars on combining new technologies and designing new phones. It is worth noting that the chipset quality plays a central role in this process. For example, several times more power is consumed by GPU and CPU than the display when a smartphone is used to play video games (Chen et al. (2013)). A smartphone maker would not be able to use large screens for its phones (more pixels for the processors to compute) without first obtaining energy-efficient chipsets.

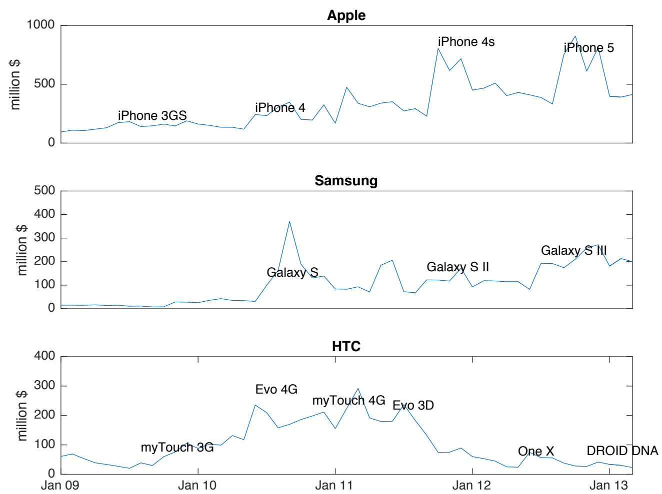
Smartphone sales are driven by the release of new products. I plot the monthly retail sales revenues in Figure 1. The sales spikes tend to coincide with the release of flagship products. The innovation of Qualcomm, marked by the release of new generation of chipsets, occurs 2 to 6 months before handset makers adopt the chipsets.

The data set includes the aggregate sales, retail prices and characteristics of smartphones sold through the four national carriers, from January 2009 to March 2013.[8] The observation is at the handset-carrier-month level. The US market accounts for about 15% of the global shipment in Q4 2011 (Gartner (2012)), but is likely more important to the high end handset makers. For example, it is reported that the US market accounted for over 40% of Apple's revenue in 2010.[9]

[8]Smartphone quantity and price data are acquired from the ITG Market Research, and the chipset information is scraped from technology websites and press releases.

[9]CSI Market.

Figure 1: Handset Maker Monthly Sales Revenues



Throughout the analysis, I assume that the US market accounts for a constant proportion of the world market. While I do not observe chipset prices directly, I collect the accounting gross margin data of Qualcomm from its quarterly financial reports. I use the data as the sales-weighted average markup of Qualcomm chipsets. The average markup data allow me to impute product-specific chipset prices, detailed in Section 5. Additional data and institutional details of the smartphone industry can be found in Fan and Yang (2016).

3 A Dynamic Model of Upstream and Downstream Innovation

Time is discrete $t = 1, 2, \ldots, T$. The upstream consists of Qualcomm and a non-strategic fringe. Downstream firms are comprised of a finite number of firms $\mathcal{N}$. The Qualcomm state variable is the quality frontier q^Q. The state variables of a handset maker n include the proportion of n's handsets using Qualcomm and n's quality frontier, $s^n = \{\eta^n, q^n\}$, $\eta^n \in (0, 1)$. The industry state consists of $s = \left\{t, q^Q, \{\eta^n, q^n\}_{n\in\mathcal{N}}\right\}$. The empirical game estimated later would include Apple and HTC whose η's are fixed, and Apple is not constrained by Qualcomm innovation. To simplify the presentation of the model, I assume in this section that all handset makers can adjust their proportions of handsets using Qualcomm, and are constrained by Qualcomm's quality frontier.

In every period, Qualcomm chooses quality increments of its quality frontier, $a^Q \in \{0, \varDelta, 2\varDelta, \ldots, K_1\varDelta\}$, and the next period Qualcomm state transitions to $q^Q_{t+1} = q^Q_t + a^Q$. The action in data that corresponds with Qualcomm innovation is its release of new chipsets. A handset maker also chooses quality increments $a^n_q \in \{0, \delta, 2\delta, \ldots, K_2\delta\}$. If n does not innovate ($a^n_q = 0$), the proportion stays the same. If n innovates ($a^n_q > 0$), n also chooses its proportion of handsets using Qualcomm from a discrete set, $a^n_\eta \in \{\eta_1, \eta_2, \ldots, \eta_{K_3}\}$, at the new quality level $q^n_{t+1} = q^n_t + a^n_q$. n's state transition can be summarized as the following: when n takes action $a^n = \left\{a^n_q, a^n_\eta\right\}$, the next period state becomes

$$\begin{cases} q_{t+1}^n = q_{t+1}^n + a_q^n, \eta_{t+1}^n = a_\eta^n, & \text{if } a_q^n > 0 \\ q_{t+1}^n = q_t^n, \eta_{t+1}^n = \eta_t^n, & \text{if } a_q^n = 0 \end{cases}$$

The action in data corresponding with handset maker n's innovation is the launch of a handset whose quality is higher than any of n's previous handsets.

The game starts in $t = 1$. In every period, firms first receive period profits $\pi_t(s_t)$, and make dynamic decisions sequentially. Qualcomm moves first, and handset makers move in the sequence $n_1, \ldots n_N$:

- Qualcomm draws i.i.d cost shock ε_t^Q, takes action a_t^Q and pays a sunk cost of $C^Q\left(a_t^Q, \varepsilon_t^Q\right)$.
- Handset maker n_1 observes Qualcomm's decision, draws i.i.d cost shock $\varepsilon_t^{n_1}$, takes action a^{n_1} and pays $C^{n_1}\left(a_t^{n_1}, \varepsilon_t^{n_1}\right)$

  ...
- Handset maker n_N observes all previous actions, draws i.i.d cost shocks $\varepsilon_t^{n_N}$, takes action a^{n_N} and pays $C^{n_N}\left(a^{n_N}, \varepsilon_t^{n_N}\right)$.

The dynamic optimization problem of Qualcomm in period t solves

$$\max_{a^Q}\left(-C^Q\left(a^Q, \varepsilon_t^Q\right) + \beta E\left(V_{t+1}^Q\left(s_{t+1}\right)|s_t\right)\right),$$

where the expectation is taken over the action probabilities of firms who have not moved in period t. The value function of Qualcomm satisfies the Bellman equation

$$V_t^Q\left(s_t\right) = \pi^Q\left(s_t\right) + \int_{\varepsilon_t^Q}\left\{-C^Q\left(a^{Q\star}, \varepsilon_t^Q\right) + \beta E\left(V_{t+1}^Q\left(s_{t+1}\right)|s_t\right)\right\}, \tag{1}$$

where the strategy $a^{Q\star}$ is a function of its own cost shock. Similarly, a handset maker n solves

$$\max_{a^n}\left(-C^n\left(a^n, \varepsilon_t^n\right) + \beta E\left(V_{t+1}^n\left(s_{t+1}\right)\middle|a_{\mathcal{N}(n)}, s_t\right)\right),$$

but subject to the constraint that $q_t^n + a_q^n \leq q_{t+1}^Q$. $a_{\mathcal{N}(n)}$ denotes the actions of firms that have moved before n. The Bellman equation of n is identical to (1), with the superscript Q replaced by n. Also note that n's strategy is a function of its shocks and the actions of firms that have moved. Players in this game have private information and move sequentially, and I solve for the Perfect Bayesian Nash Equilibrium (PBE). The last period value function is specified as $V_T = \dfrac{\pi\left(s_T\right)}{1-\beta}$.

While the assumptions of a finite horizon and sequential moves are quite strong, they provide three crucial benefits: 1) the dynamic equilibrium is unique, 2) solving the dynamic game does not involve value function iterations and suffers no convergence problem (Egesdal, Lai and Su (2015)), 3) the finite horizon assumption also helps to capture the non-stationarity in data (Igami (2015)). I explore the robustness of both assumptions in Appendix D.

The investment cost is specified as

$$C^Q\left(a^Q, \varepsilon_t^Q\right) = \begin{cases} 0, & a^Q = 0 \\ \exp\left(\gamma_0^Q + \left(\gamma_1^Q + \sigma^Q \varepsilon_t^Q\right) a^Q\right) & a^Q > 0 \end{cases}$$

$$C^n\left(a^n, \varepsilon_t^n\right) = \begin{cases} 0, & a_q^n = 0 \\ \exp\left(\gamma_0^n + \left(\gamma_1^n + \sigma^n \varepsilon_t^q\right) a_q^n + \gamma_2^n a_\eta^n\right) & a_q^n > 0 \end{cases}$$

The cost shocks ε follow the standard normal distribution.

In this model, I assume that dynamic innovation decisions are not contractible. Therefore it is not possible that HTC enters into a contract with Qualcomm about Qualcomm innovation before Qualcomm's innovation is realized. Such contracts would effectively achieve vertical integration. Grossman and Hart (1986) suggests that without investment coordination, two vertically separated firms would invest below the socially optimal level because neither firm fully internalizes the benefit of investment on the other. Central to the concept of "incompleteness" is the difficulty of communicating a firm's investment decisions to others before the realization of the investment. Indeed, while the technology capability of a firm is abstracted into a scalar q in the model, coordinating innovations in the real world potentially would require the chipset maker and handset maker to agree on the joint development of many dimensions of the technology. Identifying and agreeing to the exact nature of innovation may be hard enough. The legal costs of writing down contracts that enumerate all aspects of cooperative development could be high. Enforcement may be hard, because in the case of contract violations, firms may need to disclose proprietary designs in a legal proceeding. Given these considerations, I assume that firms cannot contract on future innovation.[10]

4 Bargaining Model

The profit function $\pi(s_t)$ is given by a static model of bargaining. I assume that prices are set in the following order:

1. Qualcomm and handset makers negotiate chipset prices via Nash bargaining.
2. Handset makers take the chipset prices and other components of the marginal cost as given, set retail prices and sell to consumers.

I start with the demand function.

[10] The ex ante communication difficulty may be overcome in an infinite horizon dynamic game. There may exist a PBE where firms condition strategies on past actions and Qualcomm may be able to credibly slow down innovation and "punish" HTC, if HTC does not pay Qualcomm a transfer after a Qualcomm innovation. The additional assumptions of a finite horizon and sequential moves rule out this possibility: the game admits a unique solution, which can be obtained via backward induction. In this equilibrium, the downstream firms would not voluntarily pay Qualcomm a transfer. These assumptions in some sense have the effect of a Markov refinement in an infinite horizon game and eliminate the cooperative equilibria.

4.1 Consumer Demand

I model the consumer demand for smartphones using a random coefficient logit model (Berry, Levinsohn and Pakes (1995)). Index consumers by i and handsets by j. The utility of consumer i purchasing handset j in period t is

$$\begin{aligned} u_{ijt} &= \beta_{0i} q_j - \alpha p_{jt} + \theta_{n(j)} + \kappa_{c(j)t} + \xi_{jt} + \epsilon_{icjt} \\ &= \underbrace{\bar{\beta}_0 q_j - \alpha p_{jt} + \theta_{n(j)} + \kappa_{c(j)t} + \xi_{jt}}_{\mu_{jt}} + \sigma \nu_i q_j + \epsilon_{ijt} \end{aligned}$$

where $q_j = x_j \beta$ is the linear quality index of handset characteristics, β_{0i} is a normally distributed scalar random coefficient that captures the heterogeneous tastes for quality: $\beta_{0i} = \beta_0 + \sigma \nu_i, \nu_i \sim \mathcal{N}(0,1)$, p_{jt} is the retail price of the smartphone, θ_n is the handset maker fixed effect, κ_{ct} is the carrier-year fixed effect plus quarter fixed effect that captures carrier service heterogeneity and the values of time-varying outside options (this term is referred to as carrier-time fixed effects in the rest of the paper), ξ_{jt} is the unobserved product quality, and ϵ_{ijt} is an i.i.d type I extreme value shock. Smartphone characteristics in x_j include the screen size, camera resolution and chipset generation fixed effects. The mean portion of the consumer utility function is collected in the term μ_{jt}, and the utility of no purchase is normalized to zero plus an i.i.d type I extreme value shock $\epsilon_{i\emptyset t}$. The demand for j is given by

$$D_{jt} = D_0 \quad \frac{\exp\left(\mu_{jt} + \sigma \nu_i q_j\right)}{1 + \sum_{j' \in \mathcal{J}_t} \exp\left(\mu_{j't} + \sigma \nu_i q_{j'}\right)} dF_{\nu_i},$$

where $\mathcal{J}_t$ is the set of all products available in period t, D_0 is the market size and F_{ν_i} is the CDF of ν_i. I next discuss the pricing of smartphones and chipsets.

4.2 Prices of the Smartphones

Denote the set of handset maker n's product as $\mathcal{J}_{nt}$. Given the chipset prices ψ_{jt} and other parts of the marginal cost ω_{jt}, handset maker n sets wholesale prices $w_{jt}, \forall j \in \mathcal{J}_{nt}$, to maximize its profit

$$\sum_{j \in \mathcal{J}_{nt}} \left(w_{jt} - \psi_{jt} - \omega_{jt}\right) D_{jt}.$$

The non-chipset marginal cost of a smartphone is specified as a function of observed characteristics plus a shock:

$$\omega_{jt} \equiv \underbrace{\lambda_q \exp\left(q_{jt}\right) + \lambda_{n(j)} + \lambda_{Q(j)} + \zeta_{c(j)t}}_{\substack{\text{quality, handset maker FE} \\ \text{use Qualcomm?} \\ \text{carrier-time FE}}} + \underbrace{\varkappa_{jt}}_{\text{shock}}. \tag{2}$$

Carrier pricing of handsets can be complex. To simplify computation, I assume that the carrier subsidy on product j is specified as

$$r_{jt} = \tilde{\lambda}_q \exp(q_{jt}) + \tilde{\lambda}_{n(j)} + \tilde{\lambda}_{Q(j)} + \tilde{\zeta}_{c(j)t} + \tilde{\varkappa}_{jt},$$

such that the retail price satisfies $p_j = w_{jt} - r_{jt}$. Handset maker n's profit maximization problem can be re-written as

$$\max_{p_{jt}, j \in \mathcal{J}_{nt}} \sum_{j \in \mathcal{J}_{nt}} (p_{jt} - \psi_{jt} - (\omega_{jt} - r_{jt})) D_{jt}.$$

Given this equivalence, I assume that handset makers choose retail prices directly. To save notation, I re-define ω_{jt} as $\omega_{jt} - r_{jt}$, and correspondingly, the coefficients in the non-chipset component λ as $\lambda - \tilde{\lambda}$ and the shock $\varkappa$ as $\varkappa - \tilde{\varkappa}$. Equilibrium retail prices satisfy the following first order condition:

$$s_{jt} + \sum_{j \in \mathcal{J}_{nt}} \left(p_{j t} - \psi_{j t} - \omega_{j t} \right) \frac{\partial s_{j t}}{\partial p_{jt}} = 0, \forall j' \in \mathcal{J}_{nt}.$$

In vector notation similar to Eizenberg (2014), the vector of retail prices p satisfies

$$p - \psi - \omega = (L * \Delta)^{-1} s, \tag{3}$$

where L is a $|\mathcal{J}_t| \times |\mathcal{J}_t|$ product origin matrix ($L_{jj} = 1$ if both j and j' belong to $\mathcal{J}_{nt}$ and 0 otherwise), Δ_{jj} is the derivative of the demand for j' with respect to the price of j, and $*$ represents element-by-element multiplication. If the price equilibrium is unique at this stage, the derived demand for chipsets on handset j is well defined. However, there may be multiple Nash-Bertrand equilibria under logit demand with random coefficients and multi-product firms (Echenique and Komunjer (2007)). To select an equilibrium, I use (3) as a fixed point mapping to solve for the equilibrium iteratively. The starting point is the price of the product in data that is closest in quality. Denote $D^\star = D(p^\star(\psi, \omega))$ as the derived demand for chipsets.

4.3 Nash Bargaining and Chipset Prices

The bargaining game in the first stage of the static game determines the equilibrium chipset prices between Qualcomm and handset makers. I first write down Qualcomm's profit function. Qualcomm earns profits from chipset sales:

$$\pi_t^Q(\psi) = \sum_{j \in \mathcal{J}_{Qt}} \left(\psi_{jt} - \underline{\psi} \right) D_{jt}^\star$$

where $\mathcal{J}_{Qt}$ is the set of handsets using Qualcomm chipsets and $\underline{\psi}$ is the marginal cost for Qualcomm to manufacture a chipset.[11] The chipset prices are set in a bargaining equilibrium. Qualcomm negotiates with each handset maker n separately. Denote the vector of chipset prices specific to a

[11] In reality, Qualcomm does not own any chipset manufacturing facility, and it outsources the production to dedicated fabrication plants.

Qualcomm-n bargaining pair as $\boldsymbol{\psi}_{nt} = (\psi_{jt}, j \in \mathcal{J}_{Qt} \cap \mathcal{J}_{nt})$.

Definition 1. Chipset prices $\boldsymbol{\psi}_{nt}$ for all products in $\mathcal{J}_{Qt} \cap \mathcal{J}_{nt}$ are set to maximize the Nash product corresponding with the bargaining pair of Qualcomm and handset maker n, conditional on other chipset prices $\boldsymbol{\psi}_{-nt}$:

$$\left[\pi_t^Q \;\; \boldsymbol{\psi}_{nt}, \boldsymbol{\psi}_{-nt} \;\; - \tilde{\pi}_t^Q \;\; \boldsymbol{\psi}_{-nt} \;\right]^{\tau_t} \cdot \left[\pi_t^n \;\; \boldsymbol{\psi}_{nt}, \boldsymbol{\psi}_{-nt} \;\; - \tilde{\pi}_t^n \;\; \boldsymbol{\psi}_{-nt})\right]^{1-\tau_t},$$

where $\tilde{\pi}$ is the disagreement payoff, and τ_t is the bargaining weight.[12]

Many papers using empirical bargaining games such as Crawford and Yurukoglu (2012), Grennan (2013) and Crawford et al. (2015) employ the assumption that, at the disagreement point, products in $\mathcal{J}_{Qt} \cap \mathcal{J}_{nt}$ are dropped, and firms earn profits from the rest of the products with the remaining products' chipset prices fixed and downstream equilibrium recalculated. In absence of Qualcomm's chipset competitors, there is reason to believe that the bargaining weight τ should be close to 0.5: Collard-Wexler, Gowrisankaran and Lee (2014) interprets the parameter as the relative discount factor, and the discount factors are likely equal across agents.[13] However, as Qualcomm's competitors are able to offer substitutable chipsets, this weight is unlikely to be 0.5. Another plausible disagreement point definition may be that, while the bargaining weight is fixed at 0.5, handset makers switch to an outside alternative temporarily. I therefore consider three types of disagreement payoffs:

1. n switches to a non-Qualcomm source and does not pay chipset prices to Qualcomm, but the qualities of products in $\mathcal{J}_{Qt} \cap \mathcal{J}_{nt}$ decrease by $\bar{q}_t$, their chipset prices are set to 0, and Qualcomm does not provide chipsets for these products. Chipset prices of other products are held fixed, and the downstream equilibrium is recalculated. $\tau_t = 0.5$. $\bar{q}_t = \bar{q} + \sigma_q \varpi_t$. ϖ_t is standard normal i.i.d across time, and $(\bar{q}, \sigma_q)$ are parameters to be estimated.

2. n switches to a non-Qualcomm source and does not pay chipset prices to Qualcomm, but procures chipsets for products in $\mathcal{J}_{Qt} \cap \mathcal{J}_{nt}$ at a price $\bar{\psi}_t$, and Qualcomm does not provide chipsets for these products. The qualities of these products do not change. Chipset prices of other products are held fixed, and the downstream equilibrium is recalculated. $\tau_t = 0.5$. $\bar{\psi}_t = \bar{\psi} + \sigma_\psi \varpi_t$. ϖ_t is standard normal i.i.d across time, and $\;\bar{\psi}, \sigma_\psi\;$ are parameters to be estimated.

3. Products in $\mathcal{J}_{Qt} \cap \mathcal{J}_{nt}$ are dropped, and firms earn profits from the rest of the products. Chipset prices of other products are held fixed, and the downstream equilibrium is recalculated. The bargaining weight is an unknown parameter $\tau_t \in (0, 1)$ to be estimated. $\bar{\tau}_t = \bar{\tau} + \sigma_\tau \varpi_t$. ϖ_t is standard normal i.i.d across time, and $(\bar{\tau}, \sigma_\tau)$ are parameters to be estimated.

[12] Crawford and Yurukoglu (2012) shows that alternative definitions of a bargaining pair do not strongly affect their counterfactual equilibrium price predictions.

[13] This parameter may also reflect differences of bargaining abilities due to, for example, information asymmetry (Grennan and Swanson (2016)).

In the bargaining equilibrium, the vector of all Qualcomm chipset prices ψ satisfies the following first order condition:

$$\psi = \underline{\psi} + \Theta^{-1}\Phi, \tag{4}$$

where Θ and Φ are defined (differently) for each bargaining model in Appendix A.[14]

It should be noted that the assumption of linear contracts between handset makers and Qualcomm is not completely innocuous. This assumption introduces double marginalization, an inefficiency that vertical integration can reduce. Unfortunately, contracts and contracting processes are confidential, and it is hard to obtain detailed information on these procurement agreements. I nonetheless was able to download from SEC a copy of modem procurement contract (with numbers redacted) between Qualcomm and a client (not a smartphone maker). The contract specifies the unit price, quantity and date of delivery. If two vertical monopolies can contract on both the price and quantity and firms have complete information about downstream demand, there may exist a contract equivalent to a lump sum transfer agreement that avoids double marginalization. On the other hand, if firms in fact only negotiate prices and the quantity is given by the demand function, the agreement is a linear contract. Without knowing which is the case, I follow the many papers in the literature of empirical bargaining games and assume that firms use linear contracts. Future work will explore alternative specifications.

4.4 Period Profit

Collect the number of products, product qualities, chipset origins, the bargaining parameter ($\bar{q}_t$, τ_t or $\bar{\psi}_t$) and carrier-time fixed effects in a vector y. Using the equilibrium selection rules above, Qualcomm and handset maker profits can be written as a function of y, demand shocks and marginal cost shocks, $\pi_t^Q(y, \xi, \varkappa)$ and $\pi_t^n(y, \xi, \varkappa)$. Note that y does not include the state variable of Qualcomm.

In this paper, I focus on how firms adjust quality frontiers, and assume that y is a realization from the distribution $g(Y;\, s_t, \theta)$: the set of products is a stationary distribution conditional on the state variables defined in Section 3.[15] The specification of $g(\cdot)$ is in Appendix B. In particular, the distribution is based on handset makers' state variables alone. As q^n increases, the highest and average qualities of n's smartphones increase; at a higher η_n, a larger number of n's handsets use Qualcomm. Firms use $\pi^Q(s_t) \equiv E_{Y,\xi,\varkappa|s_t}\ \ \pi_t^Q(Y, \xi, \varkappa)$ and $\pi^n(s_t) \equiv E_{Y,\xi,\varkappa|s_t}(\pi_t^n(Y, \xi, \varkappa))$ to make dynamic innovation decisions.

The assumptions of the static demand and pricing and the stationarity of product distribution allow the period profits to be computed separately from the dynamic game. The integration of $\pi_t^Q(Y, \xi, \varkappa)$ and $\pi_t^n(Y, \xi, \varkappa)$ over the distribution of products, demand shocks and cost shocks is time-consuming but only needs to be done once, because the random variables are distributed i.i.d over time. No knowledge of the innovation costs or the dynamic equilibrium is required to compute period profits. The profits are then taken as input to the estimation and simulation of the dynamic

[14] There may also be multiple bargaining equilibria. To define the period profit for each firm, I use (4) as a fixed point mapping to iteratively solve for the equilibrium chipset prices, starting from $1.2\underline{\psi}$.

[15] See Fan and Yang (2016) for a study on product variety.

game. In reality, smartphones may be both durable goods and network goods (Sinkinson (2014) and Luo (2015)). While the framework in this paper does not include dynamic consumers and endogenous network effects, the demand function partially captures both effects with κ_{ct}, and the model implicitly assumes that the two effects are exogenous.

5 Estimation

5.1 Demand and Smartphone Marginal Cost

Demand is estimated using standard BLP instruments on the full sample from January 2009 to March 2013. Each month is treated as an independent market. The estimates of the demand model are presented in the left panel of Table 2. The characteristics x_j used to construct the quality index include the screen size,[16] chipset generation, camera resolution, weight and the talking time on full battery. The screen size coefficient is normalized to be 1. The chipset generation fixed effect corresponds with each generation of Qualcomm chipsets and comparable products. Generation 1 corresponds with phones that do not use chipsets or use uncategorized old chipsets, and the coefficient is normalized to be 0. The brand fixed effects of Apple, Samsung and BlackBerry are also included. The detailed definitions of variables and interpretations of the coefficients are documented in Fan and Yang (2016). The demand estimates are reasonably intuitive, with higher generation, camera resolution, lower weights and longer battery talk time contributing positively to the index. The Apple brand fixed effect in the demand function is large, worth over \$400 to consumers.

Using the estimates, the quality index of a product is constructed as $q_j = x_j\beta$. I construct the quality frontier of a handset maker in period t as the highest quality in and before period t, $\max_{t\ \leq t} q_j, j \in \mathcal{J}_{nt}$. Because the sales of a handset maker are driven by its flagship products, and these flagship products often have the highest quality, this construction captures the essence of handset maker innovation. To construct the frontier corresponding with each generation's Qualcomm chipsets, I use the highest quality of handsets using that generation's chipsets plus 0.25. For example, the highest quality handset that uses generation 4 is Galaxy Note, and its quality is 7.17. The generation 4 chipset quality is then 7.42. It is possible that the observed handsets on a generation's chipsets never "reach the full potential", and a handset maker could use the chipset to produce a phone whose quality may be much higher than 7.17. My construction may seem conservative, but a 0.25 increase in quality is nontrivial, because it is almost the size of the increase of the generation coefficient from generation 2 to 3 and from 3 to 4.

I now discuss how to estimate the marginal cost function (2). Given the estimated demand function and observed prices, the full marginal cost $\omega + \psi$ can be inverted using the first order condition (3). To estimate the coefficients in (2), I need to break out the chipset prices ψ. To

[16] The screen size is measured as the diagonal length of the phone, as is standard in this industry, and the unit is inch.

Table 2: Demand Side Estimates

		Est	Se
β	Screen Size (inch)	1	-
	Chipset Generation 2	0.460	0.113
	Chipset Generation 3	0.718	0.147
	Chipset Generation 4	1.055	0.200
	Chipset Generation 5	1.674	0.280
	Camera Resolution (megapixel)	0.093	0.036
	Weight (gram)	-0.002	0.001
	Battery Talk Time (hours)	0.056	0.013
σ	Std, Quality	0.300	0.079
$\bar{\beta}_0$	Mean, Quality	0.779	0.128
α	Price ($)	0.007	0.002
θ_n	Apple	2.779	0.094
Carrier-time and other brand fixed effects included			

Table 3: Supply Side Estimates

		Model 1		Model 2		Model 3	
		Est	Se	Est	Se	Est	Se
λ_q	exp (quality/10) ($)	425.884	2.818	425.968	2.818	425.308	2.816
λ_Q	Use Qualcomm? ($)	-12.537	0.266	-12.745	0.266	-12.738	0.266
Carrier-time and brand fixed effects included							

Table 4: Bargaining Parameters and Mean Chipset Prices

Bargaining Parameter Estimates[a]								
Model 1			Model 2			Model 3		
	Est	Se		Est	Se		Est	Se
$\bar{q}$	0.222	0.015	$\bar{\psi}$ ($)	57.884	2.510	τ	0.097	0.006
σ_q	0.062	0.011	σ_ψ ($)	10.340	1.828	σ_τ	0.025	0.004
Mean Chipset Prices ($)[b]								
Model 1			Model 2			Model 3		
36.746			36.749			36.700		

[a]: mean and standard deviations are calculated from inverted $\bar{q}_t$, $\bar{\psi}_t$ or τ_t specific to each quarter on a sample of 17 quarters.

[b]: averaged over all imputed chipset prices of Samsung and HTC.

impute ψ, I rely on the average Qualcomm markup data in its quarterly financial reports[17] and the equilibrium first order conditions corresponding with the Nash product, (4). I set Qualcomm's marginal cost of manufacturing a chipset to be \$20. Consider Bargaining Model 1. For every $\bar{q}$, I can solve for a vector of chipset prices consistent with the observed retail prices using (4) in every t. If the solution is unique, then there exists a one-to-one relationship between $\bar{q}$ and the vector of equilibrium chipset prices. Because a vector of chipset prices implies a unique sales-weighted average Qualcomm chipset markup, there exists a one-to-one relationship between $\bar{q}$ and the average Qualcomm markup. I use this relationship to invert a $\bar{q}_t$ for every period. In practice, I can always obtain a unique solution when solving for the chipset prices from multiple starting points.

Table 3 shows that the marginal cost estimates from three different bargaining models are consistent. The non-chipset components' costs increase with the quality of the smartphone. Using a Qualcomm chipset saves \$12 to \$13 in marginal cost for the non-chipset part of the phone. An alternative interpretation is that it costs about \$12 to acquire a non-Qualcomm chipset. The estimates of the bargaining parameters are presented in Table 4. The financial reports I used are quarterly, and the sample includes 17 quarters. For every quarter, depending on the bargaining model, I invert a $\bar{q}_t, \bar{\psi}_t$ or τ_t by matching the (un-discounted) sales-weighted average Qualcomm markup of the quarter with the gross margin data. I assume that the random variables are normal and distributed i.i.d over quarters, and I estimate the mean and standard deviation using the 17 observations. During the inversion process, I use a minimization algorithm to match markup with data. I run the algorithm from 10 different starting points and always find a unique solution. The average Qualcomm chipset prices are about \$37. Notably, the mean bargaining weight in Model 3 is close to 0, implying that Qualcomm bargaining power is low, consistent with the fact that Qualcomm faces competition from other chipset makers.

5.2 Sunk Cost of Innovation

The estimates of the static pricing game allow me to simulate period profits at any given point in the state space. For any parameter value of the sunk cost function, I am able to solve for the unique Perfect Bayesian Equilibrium. I therefore employ a nested fixed point simulated estimator that matches moments from the model with data. To limit the computational burden, I estimate a dynamic game of Qualcomm and the three top handset makers: Apple, Samsung and HTC. I assume that the order of moves is Qualcomm, HTC, Samsung and Apple. This order is chosen so that the two firms using Qualcomm are the first to react to Qualcomm's actions. Apple is assumed to always use non-Qualcomm chipsets $\eta^A = 0$ and not constrained by Qualcomm quality frontier; HTC innovation is constrained by Qualcomm, and always chooses $\eta^{HTC} = 1$: the chipsets of all HTC phones are supplied by Qualcomm and their prices are determined in the bargaining equilibrium; Samsung innovation is also constrained by Qualcomm, but can adjust the proportion of Qualcomm chipsets used on Samsung handsets. It should be noted that Samsung uses its own

[17] This figure is defined as 1-(cost of goods sold/total revenue), which does not include fixed and sunk costs such as administrative overhead and R&D. Nevo (2001) argues that this is an upper bound on the markup.

chipsets in some of its flagship smartphones. However, these smartphones are typically launched much later than the corresponding Qualcomm generation. For example, Samsung Note II (the 5th chipset generation) using Samsung's own Exynos chipsets was launched in Oct 2012, while the corresponding generation of Qualcomm chipsets was launched in January 2012, and the first smartphone using Qualcomm's generation 5 chipsets was launched in April 2012. The model is solved by backward induction from the last period of data, March 2013. Additional details are provided in Appendix C. In Appendix D, I check the sensitivity of the assumptions of a finite horizon and sequential moves. In the first exercise, I solve the model from August 2013, with the carrier-time fixed effects in the period profit functions for April to August 2013 extrapolated from demand estimates in earlier periods. In the second exercise, I reverse the order of downstream firms' moves, and firms move in the sequence of Qualcomm, Apple, Samsung and HTC.

To underscore the importance of potential cost heterogeneity, I estimate a firm specific intercept γ_0. I also estimate a different γ_1 specific to Apple, Samsung and Qualcomm. I restrict $\gamma_1^{HTC} = \gamma_1^{Samsung}$, and I also restrict $\sigma^{Apple} = \sigma^{Samsung} = \sigma^{HTC}$ and estimate a different $\sigma^{Qualcomm}$, giving me a total of 10 parameters to estimate. I use the following moments:

1. mean innovation rates, defined as $\bar{\imath} = (q_T - q_1)/T$;
2. variance of innovation rates, $\sum_{t=1}^{T-1} (q_{t+1} - q_t - \bar{\imath})^2 /T$;
3. the mean distance from Qualcomm frontier to the maximum of HTC and Samsung's frontiers, $\sum_{t=1}^{T} \left(q_t^Q - \max \left(q_t^S, q_t^H \right) \right) /T$;
4. the mean proportion of Qualcomm chipsets on Samsung products, $\sum_{t=1}^{T} \eta_t/T$.

There are exactly 10 moments for 10 parameters: the exact identification case also helps to diagnose the performance of the minimizer of the objective function, because the minimum is 0. I use the genetic algorithm to minimize the objective function.

The moments are sensitive to the parameters. γ_0^n's are mainly identified by the mean innovation rates. Both the mean and variance of innovation rates react sharply to changes in γ_1^n. The distance between Qualcomm and the maximum of HTC and Samsung frontiers is sensitive to γ_1^Q and $\sigma^{handset}$. The mean innovation rates of Samsung and Qualcomm and the mean proportion of Qualcomm chipsets are sensitive to $\gamma_2^{Samsung}$. The mean innovation rates of Samsung, HTC and Qualcomm and the mean proportion of Qualcomm chipsets are sensitive to σ^Q.[18]

The estimates based on the period profit functions of each bargaining model are reported in Table 5. The intercept estimates γ_0 are small and close to 0 except for Qualcomm. The estimates show that increasing one unit of quality (0.25) is more costly for Apple than for Samsung and HTC, and using a higher proportion of Qualcomm chipsets reduces the innovation sunk costs. The estimates are consistent with the possibility that Qualcomm is more likely to work with a customer that primarily uses Qualcomm chipsets to reduce the handset maker's development costs.

[18]Gentzkow and Shapiro (2014) provides a (standardized) sensitivity measure to formally quantify this type of discussion.

Table 5: Estimates of Innovation Costs

Bargaining Model		1		2		3	
		Est	Se	Est	Se	Est	Se
γ_0^n	Apple	-0.28	0.22	-0.28	0.62	-0.28	0.48
	Samsung	-0.07	1.39	-0.07	1.79	-0.07	1.63
	HTC	-0.14	0.30	-0.17	0.41	-0.14	0.64
	Qualcomm	-4.78	0.68	-4.78	0.35	-4.78	0.94
γ_1^n	Apple	2.68	0.26	2.68	0.41	2.68	0.98
	HTC/Samsung	1.55	0.00	1.55	0.01	1.55	0.09
	Qualcomm	1.63	0.84	1.64	0.68	1.64	3.40
γ_2^n	Samsung	-4.00	0.93	-4.39	0.84	-4.00	0.70
σ^n	Handset Makers	1.60	0.12	1.60	0.28	1.60	0.41
	Qualcomm	0.44	0.78	0.43	0.87	0.44	0.77

To put the parameters in perspective, I simulate the dynamic model at the estimated parameter value 120 times, starting from January 2009. For the simplicity of presentation, I only discuss the results using Bargaining Model 1 (handset makers' product qualities decrease at the disagreement point); the results from the other two models are very similar. The evolution of qualities, averaged across all simulation paths, is displayed alongside the observed data in Fig. 2. The quality is adjusted for the handset maker fixed effect (adding $\frac{\theta_n}{\bar{\beta}_0}$). While the simulation does not capture the "lumpiness" of the innovation process in data,[19] it does approximate the trend reasonably well. The simulated average total investment expenditures of Apple, Samsung, HTC and Qualcomm from 2009 to 2012 are 29.71, 7.45, 3.60 and 0.69 billion dollars. To examine whether these figures are sensible, I sum up the operating expenses[20] in Apple and HTC's financial reports[21][22], discounted by an annual rate of $0.99^{12} = 0.89$. Apple and HTC's total accounting expenditures were \$41.68 and \$6.83 billion dollars during the period. As discussed earlier, the US market may account for as much as 40% of Apple revenues, and the accounting figures match the simulation in scale.

6 Counterfactual Simulation

I investigate the effects of a Qualcomm-HTC merger. HTC is a natural choice for this counterfactual because of its high dependence on Qualcomm chipsets. Moreover, Apple, the unconstrained handset maker, and Samsung, which can flexibly adjust the proportion of its handsets using Qualcomm, are a pair of downstream rival firms that would realistically react to a vertical merger. Samsung may decrease the use of Qualcomm chipsets because of the raising rivals' cost incentive,

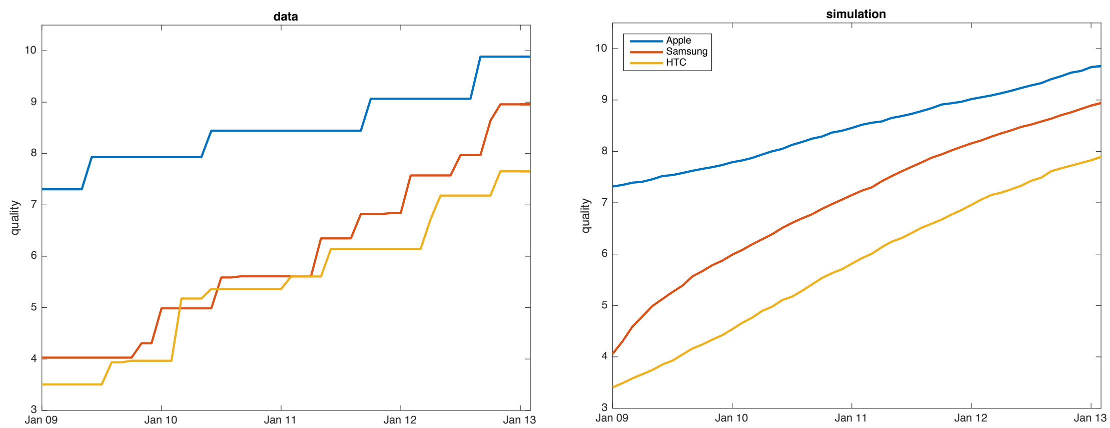
[19] Averaging across a large number of simulation paths would erase all lumpiness.

[20] This item in the financial report includes R&D, selling, general and administrative costs but does not include the manufacturing costs of the goods sold.

[21] Samsung and Qualcomm have major operations outside the application chipset and smartphone industries, and their accounting costs are less relevant.

[22] HTC's fiscal year coincides with the calendar year, and Apple's ends in September.

Figure 2: Quality Evolution, Adjusted for Handset Maker Fixed Effects



but if the integrated firm innovates faster, it may also increase its use of Qualcomm chipsets to reduce development costs and increase innovation. In the first part of the section, I simulate the effects of vertical integration and decompose the effects into the investment coordination effects and price effects. In the second part, I analyze how the parameter estimates drive the results. Specifically, I focus on the parameters that govern the upstream product (chipset) availability from non-Qualcomm producers, the substitution of the downstream products and the price sensitivity of the consumers. I simulate the baseline and every counterfactual scenario 1200 times for the period of January 2010 to December 2011, starting from the state of January 2010 in data.

6.1 Vertical Integration

Vertical integration has two effects. First, the integrated firms invest to maximize the joint value function, internalizing the marginal effect of HTC innovation on Qualcomm and vice versa. Secondly, the integrated firm reduces double marginalization within the merged parties but may raise the rival's (Samsung) costs. With the first effect, the new dynamic programming problem for Qualcomm and HTC becomes

$$\begin{array}{c} \max_{a^Q} \left\{ -C^Q\left(a^Q, \varepsilon^Q\right) + \beta E\left[V_{t+1}^{VI}\left(s_{t+1}\right) \mid a^Q, s_t\right]\right\} \\ \max_{a^{HTC}} \left\{ -C^{HTC}\left(a^{HTC}, \varepsilon^{HTC}\right) + \beta E\left[V_{t+1}^{VI}\left(s_{t+1}\right) \mid a^Q, a_{\mathcal{N}(HTC)}, s_t\right]\right\} \end{array}, \tag{5}$$

and the Bellman equation for the joint firm is

$$V_t^{VI}\left(s_t\right) = \tilde{\pi}^{VI} + E\left[-C^Q\left(a^{Q\star}, \varepsilon^Q\right) - C^{HTC}\left(a^{HTC\star}, \varepsilon^{HTC}\right) + \beta V_{t+1}^{VI}\left(s_{t+1}\right) \mid s_t\right], \tag{6}$$

where the expectation is taken over $\left(\varepsilon^Q, \varepsilon^{HTC}\right)$, the corresponding strategies of Qualcomm and HTC, and the action probabilities of their rivals. $\tilde{\pi}^{VI}$ is the sum of $\tilde{\pi}^Q$ and $\tilde{\pi}^{HTC}$, the joint equilibrium profit under vertical integration. The first order conditions that define the new equilibrium

Table 6: Counterfactual Results, Jan 2010 to Dec 2011, Model 1

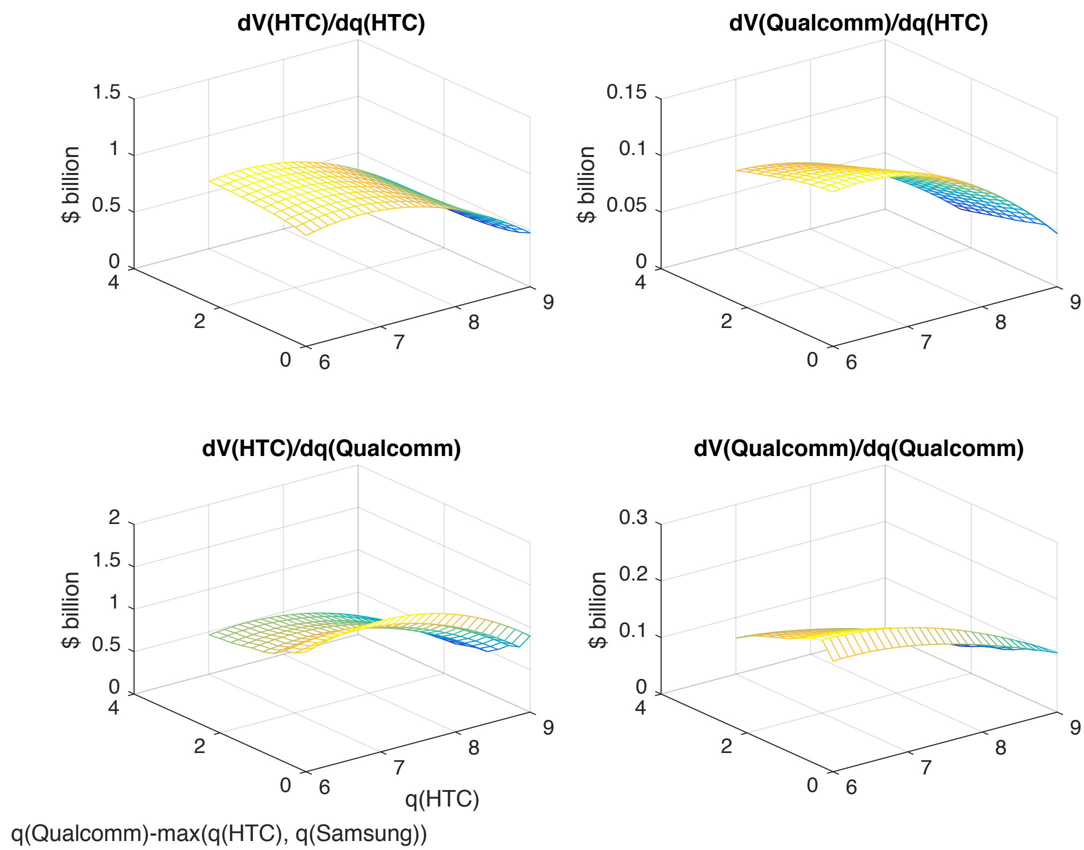
		Baseline	VI, investment coordination only	Percent Change	VI	Percent Change
Innovation Rate: $(q_T - q_1)/T$	Apple	0.06	0.07	20.69%	0.07	-0.24%
	Samsung	0.10	0.12	26.32%	0.12	1.07%
	HTC	0.10	0.12	22.59%	0.12	0.45%
	Qualcomm	0.09	0.13	38.21%	0.13	0.72%
Producer Surplus ($ billion)	Apple	11.73	12.8	9.14%	12.76	-0.29%
	Samsung	4.12	4.64	12.71%	4.67	0.54%
	HTC+Qualcomm	1.08	1.36	25.59%	1.38	1.51%
Consumer Surplus ($ billion)		16.17	18.32	13.30%	18.46	0.78%
CS+PS ($ billion)		33.1	37.12	12.16%	37.27	0.41%
% Using Qualcomm	Samsung	39.52%	51.71%	30.83%	51.88%	0.32%
Investment ($ billion)	Apple	14.02	20.11	43.45%	20.02	-0.45%
	Samsung	2.75	2.45	-10.82%	2.45	-0.09%
	HTC	1.43	2.37	65.88%	2.4	1.45%
	Qualcomm	0.30	0.73	144.08%	0.74	1.73%
Retail Price ($)	Apple	172.91	184.78	6.87%	184.52	-0.14%
	Samsung	226.92	245.19	8.05%	246.38	0.49%
	HTC	232.87	248.71	6.80%	234.82	-5.59%
Chipset Price ($)	Samsung	33.49	33.55	0.18%	34.29	2.23%
	HTC	33.19	33.28	0.25%	-	-

prices in the static pricing game are outlined in the Appendix A.

I conduct three sets of simulations: baseline, investment coordination only, and full vertical integration with both investment coordination and price effects. The purpose of the second simulation is to parse out the investment coordination effect. Specifically, I simulate the outcomes where firms still price their products as if they were still separate, but Qualcomm and HTC pool their profits when making dynamic investment decisions: i.e. I replace $\tilde{\pi}^{VI} = \tilde{\pi}^{Q} + \tilde{\pi}^{HTC}$ with $\pi^{Q} + \pi^{HTC}$. The difference between this simulation and the baseline simulation shows the net investment coordination effects, while the difference between this simulation and the full vertical integration simulation shows the additional price effects.

Table 6 reports the simulation based on static profits given by Bargaining Model 1. The first column (baseline) reports the simulation results at the estimated parameters, and the second column reports the results where Qualcomm and HTC coordinate investment but not pricing. The fourth column reports the results when Qualcomm and HTC coordinate both investment and pricing (full VI). The third column reports the percent change from the baseline to investment coordination-only, which shows the investment coordination effect of VI, and the last column reports the percentage change from investment coordination-only to the full VI case, reflecting the price effects of VI.

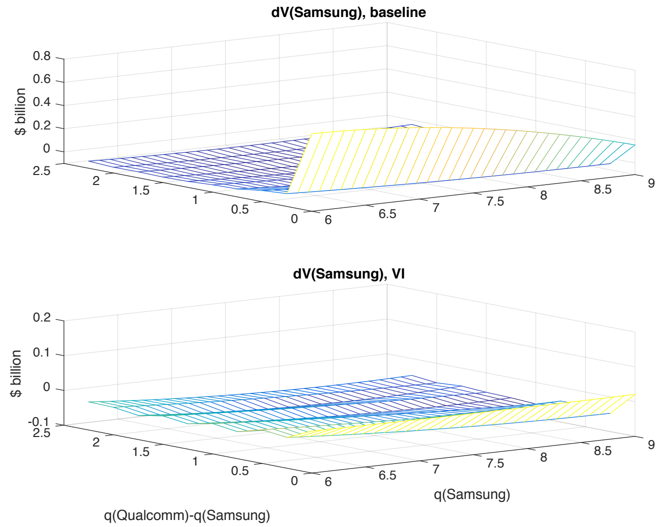
Figure 3: Marginal Effects of Qualities on HTC and Qualcomm Value Functions



The first main observation is that vertical integration substantially increases the innovation of all firms, in particular that of Qualcomm. Qualcomm and HTC innovate faster, because they each internalize the marginal value of one's innovation on the other. To visualize the magnitude of the effect, I examine the first order difference, $V(q+\delta) - V(q)$, where $\delta = 0.25$. To simplify notation, I denote the first order difference as $\frac{\partial V}{\partial q}$. I plot the baseline $\frac{\partial V^Q}{\partial q^Q}$, $\frac{\partial V^Q}{\partial q^{HTC}}$, $\frac{\partial V^{HTC}}{\partial q^Q}$, and $\frac{\partial V^{HTC}}{\partial q^{HTC}}$ in Fig. 3, where Apple and Samsung quality levels are fixed at 4.5 and 6.5. Per unit increase of Qualcomm or HTC quality, HTC value function would increase in the range of 0.5 to 1.5 billion dollars. Per unit increase of HTC quality increases Qualcomm value function by about 0.05 to 0.15 billion dollars, and the effect of Qualcomm's own quality change is slightly larger.

Samsung also innovates faster and is less constrained by Qualcomm. The average number of months that $q^{Samsung} = q^Q$ is reduced from 3.23 months to 1.25 months. Furthermore, an examination of the second order difference shows that in equilibrium, being constrained by Qualcomm is less harmful to Samsung. Denote this second order difference as $\frac{\partial^2 V^{Samsung}}{\partial q^Q \partial q^{Samsung}}$, similar to the notation above. I normalize Samsung's marginal value of innovation to 0 when Samsung is constrained. If it is profitable for Samsung to innovate, but Samsung is unable to carry it out because

Figure 4: Marginal Effect of Qualcomm Quality on the Marginal Value of Samsung Innovation



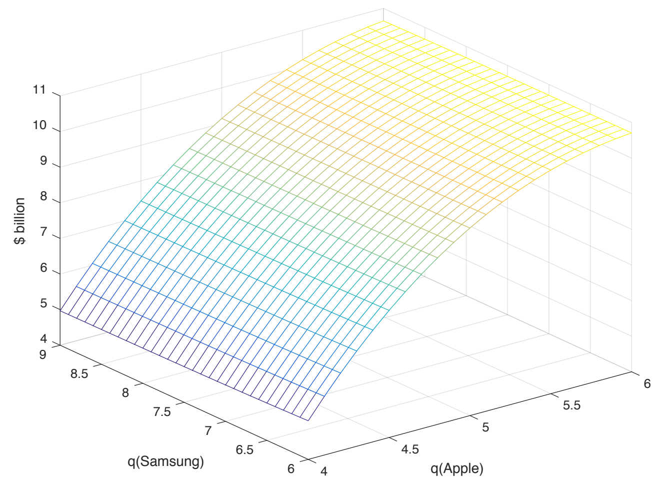
of the Qualcomm constraint, then Samsung's marginal value of innovation should increase sharply (from 0) when Samsung becomes unconstrained. In this case, $\dfrac{\partial^2 V^{Samsung}}{\partial q^Q \partial q^{Samsung}}$ should be positive, and a larger value implies greater harm from the constraint, because Samsung likely has to delay more profitable innovations. In Fig. 4, I plot the second order difference using Samsung's baseline and VI value functions. Apple and HTC qualities are fixed at 5.5 and 6, so Samsung is likely constrained if $q^Q - q^{Samsung}$ is close to 0.[23] At the baseline, the second order derivative is indeed positive and large, suggesting that Samsung is likely to miss profitable innovation opportunities when constrained. As Qualcomm innovates faster in the case of VI, the magnitude of the second order difference decreases.

Apple's faster innovation results from the long-run equilibrium changes in the competition. I plot the increase of Apple's marginal value of innovation from the baseline to the case of VI, $\left(\dfrac{dV^A}{dq^A}\right)_{VI} - \left(\dfrac{dV^A}{dq^A}\right)_{baseline}$ in Fig. 5. The quality of Qualcomm is fixed at 0.75 above Samsung, and the quality of HTC at 6. While $\left(\dfrac{dV^A}{dq^A}\right)_{VI} - \left(\dfrac{dV^A}{dq^A}\right)_{baseline}$ does not strongly respond to different levels of Samsung quality, it is large, increasing and concave in Apple quality.

The second observation is that investment coordination effects account for almost all the changes due to VI. The price effects are only about 1% of the investment coordination effects. While the magnitude is small, the price effects decrease Apple innovation while increasing other firms' innovation. The decrease of Apple innovation is intuitive, because on average, chipset prices increase with smartphone qualities, and higher quality HTC products see a larger decrease in marginal costs with the elimination of double marginalization, which may also reduce retail prices of higher

[23]Note that Samsung can be constrained even if $q^Q - q^{Samsung} > 0$: Samsung can choose the size of its quality increase, and may want to increase its quality greater than $q^Q - q^{Samsung}$.

Figure 5: Change of Apple Marginal Value Function due to the Qualcomm-HTC Merger



quality products more than of lower quality products. This downward pricing pressure thus reduces Apple's expected returns from innovation. On the other hand, Samsung is able to adjust the proportion of handsets using Qualcomm, and a higher proportion reduces innovation costs. Recall that Samsung faces the tradeoff between increasing its usage of Qualcomm chipsets, which leads to lower innovation costs, faster innovation and higher profits in the long run, and decreasing the usage of Qualcomm chipsets, which may lead to slower innovation but higher profits in the short run. The simulation shows that Samsung chooses to respond to the price effects by increasing the Qualcomm chipset usage to innovate faster. Both the investment coordination effects and the price effects reduce the overall Samsung innovation costs.

Lastly, vertical integration significantly increases consumer and producer surplus. While much of the increase comes from the investment coordination effects, the price effects also increase both surpluses. I report sales-weighted average retail prices and chipset prices (averaged over sales of handsets using a Qualcomm chipset). The elimination of double marginalization decreases HTC retail prices, while the effect of raising rivals' cost and Samsung' faster innovation (due to the price effects) increase Samsung's prices. In particular, while higher quality products may be priced higher, HTC retail prices decrease by 5.6% even when price effects increase HTC innovation.

Turning to the predictions using Bargaining Model 2 and 3 in Table 7 and 8, I find that Model 2 (replacing the Qualcomm chipset with an alternative at cost $\bar{\psi}$ at the point of disagreement) predicts changes similar in magnitudes. However, the more "traditional" Bargaining Model 3, where handset makers drop products at the point of disagreement, predicts much larger price effects of vertical integration, although the net qualitative effects are consistent with model 1 and 2. Nonetheless, this exercise suggests that researchers should conduct robustness checks or look for external validation when defining the disagreement point: different definitions of the disagreement point may generate different predictions for a counterfactual exercise, even when the models are estimated on the same data set.

Table 7: Baseline and Counterfactual Results based on Bargaining Model 2

		Baseline	VI, investment coordination only	Percent Change	VI	Percent Change
Innovation Rate: $\left(q_T - q_1\right)/T$	Apple	0.06	0.07	19.63%	0.07	-0.28%
	Samsung	0.09	0.12	29.97%	0.12	0.96%
	HTC	0.10	0.12	22.97%	0.12	0.27%
	Qualcomm	0.09	0.13	41.04%	0.13	0.55%
Producer Surplus ($ billion)	Apple	11.75	12.73	8.36%	12.7	-0.24%
	Samsung	3.9	4.6	17.92%	4.6	0.09%
	HTC+Qualcomm	1.09	1.38	26.72%	1.39	0.89%
Consumer Surplus ($ billion)		15.95	18.24	14.36%	18.35	0.63%
CS+PS ($ billion)		32.68	36.95	13.04%	37.05	0.27%
% Using Qualcomm	Samsung	37.82%	52.85%	39.73%	51.72%	-2.13%
Investment ($ billion)	Apple	13.94	19.73	41.50%	19.63	-0.50%
	Samsung	2.72	2.33	-14.39%	2.34	0.49%
	HTC	1.40	2.28	62.48%	2.31	1.29%
	Qualcomm	0.29	0.75	156.00%	0.76	1.57%
Retail Price ($)	Apple	173.00	184.09	6.41%	183.85	-0.13%
	Samsung	220.79	244.63	10.80%	244.47	-0.07%
	HTC	234.65	250.30	6.67%	235.95	-5.73%
Chipset Price ($)	Samsung	33.53	33.59	0.20%	34.25	1.96%
	HTC	33.53	33.57	0.12%	-	-

Table 8: Baseline and Counterfactual Results based on Model 3

		Baseline	VI, investment coordination only	Percent Change	VI	Percent Change
Innovation Rate: $(q_T - q_1)/T$	Apple	0.06	0.07	20.03%	0.07	-0.51%
	Samsung	0.09	0.12	32.85%	0.13	3.39%
	HTC	0.10	0.13	20.07%	0.13	2.58%
	Qualcomm	0.10	0.13	36.35%	0.13	2.04%
Producer Surplus ($ billion)	Apple	11.83	12.78	7.98%	12.66	-0.89%
	Samsung	3.57	4.58	28.23%	4.72	3.15%
	HTC+Qualcomm	1.14	1.39	22.03%	1.51	8.23%
Consumer Surplus ($ billion)		15.69	18.27	16.46%	18.57	1.66%
CS+PS ($ billion)		32.23	37.02	14.85%	37.47	1.21%
% Using Qualcomm	Samsung	45.46%	51.40%	13.06%	55.39%	7.77%
Investment ($ billion)	Apple	13.85	19.72	42.39%	19.52	-1.01%
	Samsung	2.98	2.15	-27.96%	2.32	8.14%
	HTC	1.44	2.24	55.14%	2.54	13.38%
	Qualcomm	0.32	0.76	133.08%	0.82	8.76%
Retail Price ($)	Apple	173.52	184.40	6.27%	183.59	-0.44%
	Samsung	215.48	242.97	12.76%	252.52	3.93%
	HTC	236.74	250.79	5.94%	239.18	-4.63%
Chipset Price ($)	Samsung	33.24	33.59	1.05%	40.06	19.24%
	HTC	33.28	33.50	0.66%	-	-

6.2 Comparative Statics

The previous section has shown that the effects of VI on innovation are large, positive and driven by the investment coordination effects. In this section, I explore how the parameters that govern the price effects may change the results using Bargaining Model 1. In particular, I examine the effects of three parameters: the decrease in quality at the point of disagreement $\bar{q}$, consumer taste dispersion parameter σ and the price coefficient α. Increasing $\bar{q}$ allows Qualcomm to negotiate a higher chipset prices and reduces handset maker profits. Higher σ increases the proportion of consumers with a high willingness to pay for quality, thus likely increasing demand, but it also increases substitution between similar quality products and may increase the raising rivals' cost incentives. Higher price coefficients reduce the consumption of smartphones and likely would reduce the smartphone markups and chipset prices. In the counterfactuals in Table 9, I increase one of the parameters by 10% in each of the three simulations.

At higher $\bar{q}$, the price effects either reduce innovation or have a smaller positive impact on the innovation of all handset makers. The price effects reduce the innovation of Apple from -0.24% to -0.36%, which suggests that Qualcomm's higher bargaining ability has a larger negative impact on the marginal value of rival innovation. HTC innovation attributable to the price effects is proportionally smaller, suggesting that with higher upstream bargaining ability, the marginal value of downstream innovation for the integrated firm is smaller.

The innovation rates are higher when σ is increased by 10% at the baseline, but the gains due to the vertical integration are smaller. The price effects have a larger negative impact on Apple innovation, and larger positive impact on the innovation of other firms, consistent with the intuition that price effects are stronger with a higher degree of downstream competition.

In both scenarios, differently from Table 6, Samsung uses a smaller proportion of Qualcomm chipsets even when Samsung innovation increases due to the price effects, which suggests that Samsung innovates faster not because of the savings of the innovation costs, but because of reduced payments to the integrated firm.

Increasing consumers' price sensitivity reduces the innovation rates at the baseline level, but the increase in innovation due to the investment coordination effects is similar to Table 6 in magnitude. The price effects become proportionally smaller. As consumers become more price sensitive, Qualcomm and handset makers set prices closer to the marginal cost, limiting the effects of eliminating double marginalization and raising rivals' cost.

The analysis above helps to identify situations where the price effects may affect innovation more strongly: poor upstream substitutes, high degree of downstream market competition and low consumer price sensitivity. However, even when the price effects are larger, they are unlikely to dominate the coordination effects, and do not necessarily decrease rival downstream firms' innovation.

Table 9: Comparative Statics. Innovation Rate: $(q_T - q_1)/T$

		Baseline	VI, investment coordination only	Percent Change	VI	Percent Change
$\bar{q}$	Apple	0.06	0.07	23.21%	0.07	-0.36%
	Samsung	0.10	0.12	26.68%	0.12	0.72%
	HTC	0.10	0.12	23.25%	0.12	0.07%
	Qualcomm	0.10	0.13	36.30%	0.13	1.07%
	% of Samsung using Qualcomm	36.15%	49.56%	37.12%	48.51%	-2.13%
σ	Apple	0.08	0.09	11.98%	0.09	-1.18%
	Samsung	0.10	0.12	19.51%	0.12	1.43%
	HTC	0.11	0.13	17.86%	0.13	1.17%
	Qualcomm	0.10	0.13	27.52%	0.13	1.06%
	% of Samsung using Qualcomm	36.76%	55.57%	51.18%	55.25%	-0.57%
α	Apple	0.05	0.05	3.70%	0.05	0.00%
	Samsung	0.07	0.11	50.12%	0.11	0.62%
	HTC	0.08	0.11	39.91%	0.11	0.47%
	Qualcomm	0.07	0.12	72.46%	0.12	0.58%
	% of Samsung using Qualcomm	37.15%	44.88%	20.81%	44.97%	0.20%

7 Discussion and Conclusion

This paper estimates a new model that combines bilateral bargaining with dynamic innovation to analyze the impact of vertical integration on innovation, pricing and welfare in the chipset and smartphone industry. Using the estimated model, I simulate the counterfactual experiment of a vertical merger, and find that vertical integration increases innovation primarily through the channel of investment coordination. The results suggest that the dynamic effect of vertical integration may be large, providing support for giving more weight to this factor a in a vertical merger review.

Several simplifying assumptions underlie the model. Most importantly, I abstract away from vertical integration's effects on the cost primitives. Given the possibility of cost reduction in the case of a successful merger, the results here are a lower bound on the positive impact of vertical integration. Secondly, I model the pricing game without considering the strategic roles of carriers. This modeling choice is largely motivated by the need to simplify the computation of period profits. In some sense the approach follows the CPU literature such as Goettler and Gordon (2011) and Nosko (2014) that abstracts from the role of downstream computer assemblers. An alternative handset-carrier pricing model[24] would affect the estimates of firm profits, but I do not expect the bias to reverse the result: the investment coordination is orders of magnitudes larger than the price effect. Thirdly, I do not consider serially correlated unobserved cost variables, which may be a concern given that the data frequency is monthly. Omitting these variables would

[24] As those considered in Villas-Boas (2007), Bonnet and Dubois (2010) and Fan and Yang (2016), for example.

bias the estimates of the innovation costs. However, including such a cost component does not change any of the economic argument why innovation increases with a vertical merger. Fourthly, I assume that Qualcomm and handset makers use linear contracts. Linear contracts introduce double marginalization, but these effects are likely small compared with the investment coordination effect. The paper also does not discuss patent issues in this industry. Qualcomm collects percentage fees (1 to 5%) of the wholesale smartphone prices because of its many communication technology patents. These fees form a large part of the overall Qualcomm profits, but are not directly related to Qualcomm's efforts in application chipset innovation. Lastly, vertical integration may also affect innovation through an information channel: during product development, downstream firms may need to interact with upstream firms, and vertical integration could change the integrated firm's incentive to protect or exploit the proprietary information of rival downstream firms (Allain, Chambolle and Rey (2011)). The integrated firm may imitate its downstream rivals and equilibrium innovation rates may be reduced.

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Appendix

A First Order Conditions in the Static Pricing Game

I omit the time subscript. Qualcomm and handset maker n bargain over ψ. Handset maker n's profit at the point of disagreement is

$$\tilde{\pi}^n = \begin{cases} {}_{j\in\mathcal{J}_n} \left(\tilde{p}_j - \omega_j\right) \tilde{D}_j, & \text{Bargaining Model 1} \\ {}_{j\in\mathcal{J}_n\cap\mathcal{J}_Q} \quad \tilde{p}_j - \omega_j - \bar{\psi} \quad \tilde{D}_j + \quad {}_{j\in\mathcal{J}_n\setminus\mathcal{J}_Q} \left(\tilde{p}_j - \omega_j\right) \tilde{D}_j, & \text{Bargaining Model 2} \\ {}_{j\in\mathcal{J}_n\setminus\mathcal{J}_Q} \left(\tilde{p}_j - \omega_j\right) \tilde{D}_j, & \text{Bargaining Model 3} \end{cases}$$

and Qualcomm's disagreement profit is

$$\tilde{\pi}^{Q} = \sum_{j \in \mathcal{J}_n \setminus \mathcal{J}_Q} \tilde{\psi}_j - \underline{\psi} \quad \tilde{D}_j,$$

where $\tilde{\cdot}$ denotes the recalculated equilibrium quantities at the point of disagreement.

The first order condition of the bargaining game is

$$\psi = \underline{\psi} + \Theta^{-1}\Phi,$$

where Θ and Φ are given by the following:

$$\Theta = d\Pi + d\Gamma,$$

$$\Phi = -\left(s_Q + d\Omega\right),$$

where in vector and matrix notation,

$$d\Pi = \nabla D_p \nabla p_\psi * L^Q,$$

where L^Q is a binary matrix such that $L^Q_{i,j} = 1$ if i, j both use Qualcomm chipsets, and 0 otherwise, and

$$d\Gamma = \begin{pmatrix} \frac{\partial \pi^{n=1}}{\partial \psi_{n=1}} & & \\ & \ddots & \\ & & \frac{\partial \pi^{n=N}}{\partial \psi^c_{n=N}} \end{pmatrix} \begin{pmatrix} |\mathcal{J}_Q \cap \mathcal{J}_{n=1}| \text{ replications } \left\{ \frac{\boldsymbol{D}_Q - \tilde{\boldsymbol{D}}_Q\left(n=1\right) \cdot \imath_{n=1}}{\pi^{n=1} - \tilde{\pi}^{n=1}} \right. \\ \vdots \\ |\mathcal{J}_Q \cap \mathcal{J}_{n=N}| \text{ replications } \left\{ \frac{\boldsymbol{D}_Q - \tilde{\boldsymbol{D}}_Q\left(n=N\right) \cdot \imath_{n=N}}{\pi^{n=N} - \tilde{\pi}^{n=N}} \right. \end{pmatrix},$$

where $\frac{\partial \pi_n}{\partial \psi_n}$ is a block of diagonal matrix, the derivative of handset maker n's profit with respect to the price of each of its Qualcomm chipset:

$$\frac{\partial \pi_n}{\partial \psi_i} = \sum_{j \in \mathcal{J}_{nt}} \frac{\partial p_j}{\partial \psi_i} D_j - D_i + \sum_{j \in \mathcal{J}_{nt}} \left(p_j - \omega_j - \psi_j\right) \sum_k \frac{\partial D_j}{\partial p_k} \frac{\partial p_k}{\partial \psi_i}.$$

and $\tilde{\boldsymbol{D}}_Q\left(n\right)$ corresponds with the vector of demand for Qualcomm chipsets at the disagreement point in the Qualcomm-n bargaining pair. $\imath_n$ is a row vector of binaries corresponding with each product, and equal to 0 if corresponding with firm n's products.

When Qualcomm is integrated with $\breve{n}$, the FOC's of the bargaining equilibrium becomes

$$\psi = \underline{\psi} + \Theta^{-1}\breve{\Phi}$$

where $\breve{\Phi} = -\left(D_Q + d\Lambda + d\Omega\right)$, and

$$d\Lambda = \boldsymbol{D}'_{\breve{n}} \frac{\partial \boldsymbol{p}_{\breve{n}}}{\partial \psi} + \left[\boldsymbol{p}_{\breve{n}} - \boldsymbol{\omega}_{\breve{n}} - \boldsymbol{\psi}_{\breve{n}}\right] \nabla D_p \nabla p_\psi,$$

$$d\Omega = \begin{pmatrix} \frac{\partial \pi_{n=1}}{\partial \psi_{n=1}} & & \\ & \ddots & \\ & & \frac{\partial \pi_{n=N}}{\partial \psi_{n=N}} \end{pmatrix} \cdot \begin{pmatrix} |\mathcal{J}_Q \cap \mathcal{J}_{n=1}| \text{ replications} & \frac{\pi^{\check{n}} - \tilde{\pi}^{\check{n}}(n=1)}{\pi^{n=1} - \tilde{\pi}^{n=1}} \\ \vdots & \\ |\mathcal{J}_Q \cap \mathcal{J}_{n=N}| \text{ replications} & \frac{\pi^{\check{n}} - \tilde{\pi}^{\check{n}}(n=N)}{\pi^{n=N} - \tilde{\pi}^{n=N}} \end{pmatrix},$$

where $\tilde{\pi}^{\check{n}}(n)$ corresponds with $\check{n}$'s profit at the disagreement point of Qualcomm-n pair. In addition, the integrated Qualcomm would only negotiate chipset prices with non-integrated downstream rivals.

B Product Set Simulation

I estimate a stationary distribution of product characteristics given the state variables of handset makers. I first estimate the frequency that a combination of carriers would be given the highest quality (frontier) products for each handset maker. Next, I estimate a handset maker specific distribution of the number of products below the frontier on each carrier using a Poisson distribution. I then estimate, again separately for each handset maker, the distribution of quality differences between adjacent products, where products on each carrier are ordered by quality. The differences are modeled as i.i.d shifted and scaled normal random variables. Finally, I estimate which Samsung products will use Qualcomm chipsets. Given the proportion η and the number of products $\|J_n\|$, a total of $|\|J_n\| \cdot \eta|$ products will use Qualcomm chipsets. I estimate a score function $\varpi z_j + \epsilon_j$ for each products, where products with scores in the top $|\|J_n\| \cdot \eta|$ would be given a Qualcomm chipset, where $|\cdot|$ means integer rounding. I include product qualities, the proportion η and carrier fixed effects in z_j. I estimate the score function using a simulated maximum likelihood estimator. Using the estimates, I simulate 50 sets of products for a set of handset maker state variables and use the average firm profits as π in the dynamic game.

C Solving the Dynamic Game

I set the quality increment for Qualcomm to be $\Delta = 0.5$, and $a^Q \in \{0, \mathit{\Delta}, 2\mathit{\Delta}, 3\mathit{\Delta}\}$. The handset makers' quality increment is $\delta = 0.25$, with $a_q^n \in \{0, \delta, 2\delta, 3\delta\}$ and $a_q^{Samsung} \in \{10\%, 30\%, 50\%, 70\%\}$. The specification matches most of the actions observed in data. Because of the constraint that Samsung and HTC qualities do not exceed Qualcomm's quality, I track the difference between Qualcomm and the maximum of HTC and Samsung's quality frontiers, $\delta^Q = q^Q - \max\left\{q^{Samsung}, q^{HTC}\right\} \geq 0$, instead of Qualcomm quality frontier directly, in addition to handset makers' quality frontiers and Samsung's proportion of handsets using Qualcomm chipsets. The value function is parameterized as a third degree complete polynomial of Apple, Samsung and HTC's quality levels. To precisely calculate the value function given δ^Q, η and t, I compute a different set of polynomial coefficients specific to each combination of $\left\{t, \eta, \delta^Q\right\}$, where $t = 1, \ldots, T$, $\eta \in \{10\%, 30\%, 50\%, 70\%\}$, and $\delta^Q \in \{0, \delta, \ldots, 10\delta\}$. I solve the value functions at the zeros of the Chebyshev polynomials and

Table 10: Estimates of Innovation Costs

	Robustness	Long Horizon		Reversed Order	
		Est	Se	Est	Se
γ_0^n	Apple	-0.25	0.48	-0.25	0.48
	Samsung	-0.07	1.63	-0.02	1.30
	HTC	-0.19	0.64	-0.14	1.44
	Qualcomm	-4.72	0.94	-4.72	1.39
γ_1^n	Apple	2.69	0.98	2.67	0.88
	HTC/Samsung	1.65	0.09	1.60	0.09
	Qualcomm	1.60	3.40	1.56	3.52
γ_2^n	Samsung	-4.00	0.70	-4.97	0.57
σ^n	Handset Makers	1.59	0.41	1.60	0.40
	Qualcomm	0.44	0.77	0.44	0.77

interpolate the value functions at other states. The choice probabilities of each firm are simulated with 200 draws of investment cost shocks.

D Robustness Checks

In this section I explore the robustness of two assumptions on the dynamic game: the game ends in period T, and firms move sequentially in the order of Qualcomm, HTC, Samsung and Apple. To test if the predictions are sensitive to the finite horizon assumption, I consider extending the time horizon and that the game ends in period $T + \Delta T$, with the time fixed effects in the demand function from $T + 1$ to $T + \Delta T$ extrapolated from the demand estimates in earlier periods. I have $T = 51$ in data, and I use $\Delta T = 5$. For the sequential move assumption, I estimate and simulate the original model, with handset makers moving in the reversed order: Qualcomm, Apple, Samsung and HTC. Both robustness checks are based on Bargaining Model 1.

Table 10 reports the estimates. Table 11 and 12 report the counterfactual results. Both the estimates and counterfactual predictions are very similar to the specification in the main text.

Table 11: Counterfactual Result, Long Horizon

		Baseline	VI, investment coordination only	Percent Change	VI	Percent Change
Innovation Rate: $(q_T - q_1)/T$	Apple	0.06	0.07	20.05%	0.07	-0.21%
	Samsung	0.08	0.13	52.13%	0.13	0.70%
	HTC	0.10	0.12	24.91%	0.12	0.43%
	Qualcomm	0.09	0.13	46.94%	0.13	0.49%
Producer Surplus ($ billion)	Apple	11.76	12.55	6.68%	12.51	-0.34%
	Samsung	3.42	5.03	47.21%	5.08	0.84%
	HTC+Qualcomm	1.04	1.37	31.91%	1.4	1.88%
Consumer Surplus ($ billion)		15.29	18.55	21.26%	18.7	0.83%
CS+PS ($ billion)		31.52	37.5	18.99%	37.68	0.48%
% Using Qualcomm	Samsung	41.96%	55.20%	31.57%	55.68%	0.86%
Investment ($ billion)	Apple	13.76	19.54	42.02%	19.45	-0.43%
	Samsung	2.34	1.85	-20.76%	1.88	1.82%
	HTC	1.34	2.48	85.56%	2.52	1.58%
	Qualcomm	0.28	0.76	168.27%	0.77	1.32%
Retail Price ($)	Apple	172.75	182.83	5.84%	182.53	-0.16%
	Samsung	209.91	255.89	21.91%	257.8	0.74%
	HTC	231.04	247.45	7.10%	233.86	-5.49%
Chipset Price ($)	Samsung	33.40	33.63	0.71%	34.38	2.22%
	HTC	33.23	33.26	0.09%	-	-

Table 12: Counterfactual Results, Reversed Order

		Baseline	VI, investment coordination only	Percent Change	VI	Percent Change
Innovation Rate: $(q_T - q_1)/T$	Apple	0.06	0.07	16.25%	0.07	-0.22%
	Samsung	0.09	0.11	33.76%	0.12	0.93%
	HTC	0.10	0.12	24.83%	0.12	0.45%
	Qualcomm	0.09	0.13	37.27%	0.13	0.66%
Producer Surplus ($ billion)	Apple	11.87	12.62	6.32%	12.57	-0.38%
	Samsung	3.53	4.34	22.93%	4.36	0.52%
	HTC+Qualcomm	1.06	1.38	29.93%	1.4	1.64%
Consumer Surplus ($ billion)		15.56	17.74	14.00%	17.88	0.78%
CS+PS ($ billion)		32.02	36.07	12.66%	36.21	0.38%
% Using Qualcomm	Samsung	41.08%	53.86%	31.12%	54.30%	0.81%
Investment ($ billion)	Apple	13.70	18.49	34.97%	18.4	-0.48%
	Samsung	1.73	1.67	-3.58%	1.66	-0.17%
	HTC	1.36	2.34	72.18%	2.39	2.08%
	Qualcomm	0.30	0.73	143.26%	0.75	1.66%
Retail Price ($)	Apple	173.60	182.33	5.03%	181.98	-0.20%
	Samsung	212.62	238.24	12.05%	239.68	0.61%
	HTC	231.59	248.6	7.35%	234.82	-5.54%
Chipset Price ($)	Samsung	33.41	33.53	0.35%	34.3	2.29%
	HTC	33.21	33.31	0.29%	-	-