Could Vertical Integration Increase Innovation?

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Abstract

This paper studies the effects of vertical integration on innovation in the chipset and smartphone industries. 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 increase innovation rates and social welfare, driven primarily by the investment coordination of the two merged firms.

1 Introduction

In vertical industries, upstream and downstream innovations are often complementary. Upstream firms upgrade the core technology essential to performance enhancement, and downstream firms combine the technology with innovative designs in new consumer products. Examples of complementary innovations include traction batteries (upstream) and electric vehicles (downstream), CPU's (upstream) and personal computers (downstream) and chipsets (upstream) and smartphones (downstream). This paper studies how vertical integration affects innovation, pricing and welfare.

A large body of theoretical literature has examined the investment and price effects of vertical integration. A non-exhaustive list of surveys includes Perry (1989), Holmström and Roberts (1998), Tirole (1999), Riordan (2008) and Aghion and Holden (2011). Vertical integration may be pro-investment by aligning the investment incentives of the merged firms, but the impact on other downstream competitors depends on two additional factors. First, faster upstream innovation lifts the technology ceiling, allowing downstream firms to develop better quality products. Secondly,

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faster innovation of the integrated downstream firm reduces both the pre-innovation and post-innovation profits of its competitors. Because the marginal value of innovation is the difference of these two profits, it is an empirical question whether these downstream firms would innovate faster. The second effect is similar to the economics behind how competition affects innovation (Aghion et al. (2005)).

Vertical integration also produces the well known efficiency trade-off between two pricing forces: reduced double marginalization allows the integrated downstream firm to charge consumers lower prices, but the integrated upstream firm has an incentive to charge higher prices to the downstream rivals (raising rivals' cost or the foreclosure effect). The two effects are likely to increase the profits of the merged firms and reduce the profits of the downstream rivals, both before and after innovation. Similar to the discussion above, how the two pricing forces affect innovation is also an empirical question.

Understanding the relative magnitudes and the interaction of the investment and price effects is crucial for policy and regulation. For example, the potential trade-off 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".[1] 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.

The chipset and smartphone industries provide an interesting setting to study complementary innovations. The chipset[2] includes the CPU of a smartphone, but may also combine the functions of the GPU, modem and other components (Yang et al. (2014)). Chipset quality determines a smartphone's key metrics, such as the computing power (CPU), network support (modem), graphic rendering (GPU) and energy efficiency. The innovations of chipsets center on improving these metrics without significantly increasing manufacturing costs (Yeap (2013)). New chipsets allow handset makers to improve other hardware. For example, in order to increase the screen size or display resolution, handset makers need to find additional computational power to render high definition graphics without quickly draining the battery or overheating the phone, which is only possible with more advanced chipsets (Chen et al. (2013), Phone Arena (2015)). Furthermore, chipset innovation may directly add new features to a phone. For example, Qualcomm's 805 chipsets significantly reduced the time a phone needs to be fully charged (Savov (2014)).

I use a dynamic game of investment to model the innovations of the chipset and handset makers.

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

[2]Sometime a smartphone modem is also called a communication chipset. Throughout this paper a chipset always means the application processor chipset, or system-on-chip (SoC).

The main novelty is that both upstream and downstream firms are dynamic. The upstream industry consists of a dominant firm ("Qualcomm") and a non-strategic fringe, and the downstream firms are a finite number of handset makers. Qualcomm invests to increase the quality of its chipsets. Downstream handset makers invest to increase the quality of their handsets, but some handset makers are constrained by Qualcomm and cannot increase their handset qualities above Qualcomm's chipset quality. Handset makers also choose the proportion of their 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 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 and set wholesale prices. 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 innovation decisions form a Perfect Bayesian Equilibrium.

I estimate the model using data from the US smartphone market from 2009 to 2013. The 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, 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 equilibrium pricing conditions and data on chipset markups. The first two steps do not involve estimating the dynamic model. The estimates and the pricing equilibrium assumption imply the period profit functions of the 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 innovation cost function. To keep the computation tractable, I estimate a dynamic game among the upstream Qualcomm and three handset makers: Apple, Samsung and HTC. 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 a Simulated Minimum Distance estimator to estimate the model. 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. I later perform robustness checks on these assumptions.

I examine the counterfactual should Qualcomm merge with HTC, a key handset maker that primarily uses Qualcomm chipsets. The vertical integration allows Qualcomm and HTC to jointly make innovation decisions. This treatment follows the view that vertical integration facilitates the transfer of knowledge input between the merged firms (Atalay, Hortaçsu and Syverson (2014), Natividad (2014)). In the main specification, I find that the upstream Qualcomm's innovation rate, defined as the average increase of quality per period, increases by 13% to 35%, and the innovation rate of the integrated HTC increases by 14% to 20%. Moreover, Samsung is less constrained by Qualcomm, and Samsung's innovation rate increases by 9% to 22%. Apple's innovation rate changes by less than 3%. Consumer surplus increases by 4% to 8%. I decompose the net effects into investment effects and price effects. The investment effects dominate the price effects. 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 findings thus suggest that vertical integration policies should fully take into account a vertical merger's dynamic implications and in particular the investment effects, which may be much larger than the price effects. The qualitative patterns are robust across a number of alternative specifications.

The model is grounded in the theory of incomplete contract (Grossman and Hart (1986) and Hart and Moore (1990)). Specifically, I assume that Qualcomm and handset makers neither contract on the outcomes of innovation ex ante nor cooperate tacitly. A complete contract or tacit cooperation between Qualcomm and HTC could effectively achieve vertical integration, but such an arrangement may be unlikely in this context. First, this industry is new, and the chipset technologies are complex and rapidly improving. Firms face many unforeseen contingencies. Month-to-month adjustment of smartphone product lines (Fan and Yang (2016)) also contributes to this difficulty. Non-HTC handset makers that use Qualcomm chipsets may also be concerned about the safety of their proprietary designs if Qualcomm and HTC have a contract that coordinates their innovative activities (Allain et al. (2011)). Furthermore, the ability to design in-house chipsets seems to be a desirable goal for many handset makers. Technology commentators extol how Apple's custom-designed chipsets deliver superior performance compared with other handsets that use general-purpose chipsets from Qualcomm (Colon (2013), Bradshaw (2015) and Smith (2015)). Recognizing the potential performance advantage of custom-made chipsets, handset makers either maintain (like Samsung) or are trying to start their own chipset divisions (LG, Sony and Chinese handset makers like Xiaomi and Huawei), to varying degrees of success (Sohail (2015) and Low (2017)). Formally identifying the degree of cooperation requires excluded demand shifters not available in my data. I instead use accounting investment and cost data in financial reports to provide evidence that the assumption of incomplete contract is appropriate.

Related Literature and Contributions 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)).

Compared with the existing literature, the key modeling innovation in this paper is the specification of dynamic upstream and downstream firms in a vertical industry. In addition, I also highlight a data difficulty that Qualcomm's chipset quality is not directly observed. Data only provide quality measures of observed handsets, while the relevant measure for Qualcomm's chipset quality is the maximum quality of a phone that a Qualcomm chipset would enable a handset maker to design. I overcome this difficulty by imposing bounds on Qualcomm qualities and using a Simulated Minimum Distance estimator with an inequality constraint. The estimator is based on Shi and Shum (2015) and results in a confidence set of innovation cost parameters. I sample points from the confidence set to conduct counterfactual simulations and the predictions are reasonably precise.

Closely related to this paper, Crawford, Lee, Whinston and Yurukoglu (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: 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 profits of itself and downstream firms, and Qualcomm is solely motivated to innovate by the expectation that downstream firms will innovate and adopt Qualcomm chipsets in the future. Firm dynamics are important to rationalize the data. When dynamic incentives are significantly weakened (the discount rate set far below 1) in one robustness analysis, I obtain implausible estimates for the innovation cost parameters.

Road Map In the rest of the paper, I first describe the market structure 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. Section 6 reports the counterfactual experiments. Section 7 considers two main robustness checks, and additional robustness analysis is available in Appendix D.

Table 1: Chipset Origin, % of Quantity, 2009 to 1st Quarter 2013

	Qualcomm	Samsung	TI	NVIDIA	Other
Samsung	47.55	48.96	2.63	0.61	0.25
HTC	98.30	0.00	1.48	0.08	0.14
BlackBerry	48.15	0.00	0.00	0.00	51.85
Motorola	20.81	0.00	64.98	9.85	4.36
LG	92.67	0.00	5.37	1.96	0.00

2 Industry and Data

Qualcomm is the most important upstream chipset producer. Qualcomm sells most of its application processor chipsets to non-Apple handset makers, because Apple is vertically integrated and exclusively uses its own chipsets. 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. 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.[3]

Qualcomm innovation corresponds with the releases of a new generation of chipsets. A majority of chipsets in the generation Snapdragon S1 were released in October 2008. Qualcomm chipset generations Snapdragon S2, S3 and S4 were released in April 2010, October 2010 and January 2012. Qualcomm Snapdragon S4 is the last generation observed in the data. Products in a later generation feature significant gains in performance (more cores and higher frequency) and energy efficiency.

Qualcomm also competes with several other chipset producers. Qualcomm's main competitors include Samsung's chipset division (South Korea), MediaTek (Taiwan), Texas Instruments (US) and NVIDIA (US). Table 1 reports the origins of chipsets used in major non-Apple handset makers. Compared with other chipset producers, Qualcomm is able to combine more more functionalities onto its chipsets, and Qualcomm claims that (for example, in Cheng (2012)) this design could enhance performance and extend battery life.

I divide all chipsets into 5 generations, with the chipsets released before Qualcomm S1 as the 0th generation, and the rest into 4 generations consistent with Qualcomm chipsets. I classify non-Qualcomm chipsets based on the number of cores on the chipset, the clock speed of cores and a variety of benchmark scores. Taking January 2009 as month 1, I document when Qualcomm announced the availability of a generation's chipsets and when a handset maker released a phone using that generation's chipset (not necessarily Qualcomm's) in Table 2. Apple relies on its own proprietary chipsets, and a new generation of chipsets is used in a new generation of iPhones. Other handset makers also use the latest chipsets in their new flagship phones, but they rely on

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

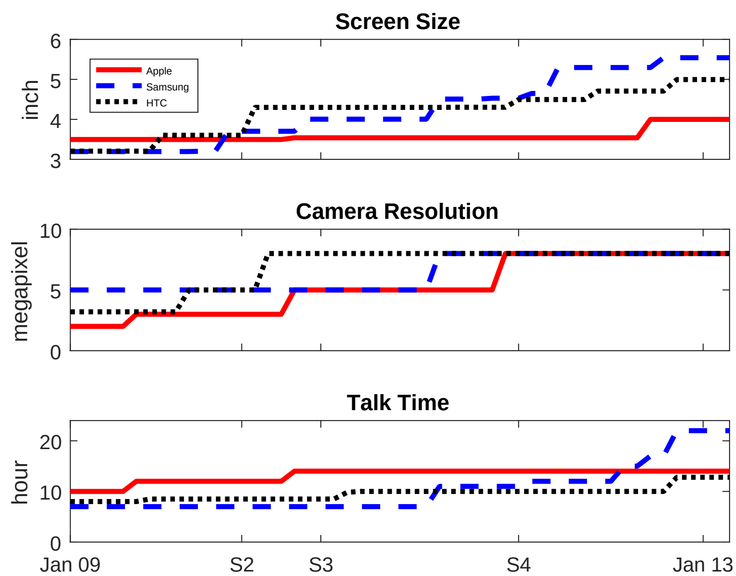
Table 2: Chipset Announcement and Adoption

	Qualcomm	Apple[a]	Samsung	HTC
Qualcomm S1 or equivalent	-4	6	6	7
Qualcomm S2 or equivalent	14	18	19	22
Qualcomm S3 or equivalent	20	34	33	30
Qualcomm S4 or equivalent	35	45	43	40

Month 1: Jan 2009

[a]: Apple uses its own chipsets and the adoption corresponds with the release of new Apple products.

Figure 1: Product Attribute Trends



Qualcomm at least partially to supply new chipsets for their phones. For example, while Samsung used its own chipsets (Exynos) for Galaxy S2 sold in the US market, Samsung still used Qualcomm chipsets for the same phone sold in China. While the release timings of these alternative chipsets are not available, Qualcomm usually release its chipsets more than 5 months before the release of non-Apple phones that use the same generation's chipsets.

New and better smartphones arrive on the market around the year. Several key dimensions of smartphone qualities, in addition to the generations of chipsets, include the size of the screen (measured by the diagonal length in inches), the resolution of the camera (megapixel) and the maximum talk time (hours) when the phone is fully charged. In Figure 1, I plot the maximum screen size, camera resolution and talk time of all products by Apple, Samsung and HTC in every month. All three measures increase over time.

Smartphone quantity and price data are from ITG Market Research, and the information on a phone's chipset and other characteristics is scraped from technology websites and press releases. The data set covers smartphones sold in the US through the four national carriers from January 2009 to March 2013. The observation is at the handset-carrier-month level. In Table 3, I document the retail revenues and quantity sold by the major handset makers for all generations and the more advanced generations. While BlackBerry sold many low-end handsets in the first year of the data, its sales decreased sharply in later years. Apple, Samsung and HTC account for 70% of sales (quantity) in the sample, and the top 5 producers in Table 3 account for 95%. 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, CSIMarket (2014) reports that the US market accounted for 37% of Apple's revenue in 2014. 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. The gross margin is defined as

$$\frac{\text{chipset sales} - \text{cost of chipsets}}{\text{chipset sales}},$$

where the cost of chipsets includes manufacturing, handling, inventory and other costs. Investment and fixed costs (in the accounting sense) are not included. 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. The average gross margin over 17 quarters from January 2009 to March 2013 is 46%, with a maximum of 60% and a minimum of 33%. There are two caveats in using accounting data. First, these figures may not reflect the true economic costs. In addition, Qualcomm also sells wi-fi chips and standalone modems, and financial reports do not itemize the gross margins by the types of chipsets. I therefore conduct robustness checks by perturbing the gross margin data in Appendix D. One additional complication is that some of these standalone modems are sold to Apple and other handset makers. I discuss how this may affect my analysis in Section 7.

Qualcomm owns a large number of patents, and collects royalties as a percentage of a phone's wholesale prices. Because virtually every phone in the world uses Qualcomm's patents, every phone maker pays such fees to Qualcomm, even if the phone maker does not use Qualcomm chipsets. Qualcomm agreed to "Fair, Reasonable and Non-discriminatory" royalty rates when Qualcomm patents were adopted as industry standards and widely used, but differences in fee levels exist (Geradin et al. (2012)). These fees do not enter the gross margin calculation above. I check whether results are robust to the presence of royalties in Section 7.

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

Table 3: Total Quantity (Million) and Retail Revenues ($ Billion)

	Quantity		Retail Revenue	
	All Generations	Generation S1-S4	All Generations	Generation S1-S4
Apple	101.35	94.79	14.18	13.57
Samsung	38.97	37.83	4.60	4.51
HTC	30.58	24.67	3.98	3.26
BlackBerry	31.03	3.15	3.43	0.34
Motorola	23.28	20.55	3.34	3.09
LG	13.68	12.83	0.92	0.87

Jan 2009 to Mar 2013 on AT&T, Sprint, T-Mobile and Verizon in US

handsets using Qualcomm and n's quality frontier, $s^n = \{\eta^n, q^n\}$, $\eta^n \in (0,1)$. The industry state consists of $s = \left\{t, q^Q, \{\eta^n, q^n\}_{n \in \mathcal{N}}\right\}$. In the empirical game estimated later, η's of Apple and HTC 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 the quality increment of its frontier, $a^Q \in \{0, \mathit{\Delta}, 2\mathit{\Delta} \ldots, K_1 \mathit{\Delta}\}$, 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

$$\begin{cases} q^n_{t+1} = q^n_{t+1} + a^n_q, \eta^n_{t+1} = a^n_\eta, & \text{if } a^n_q > 0 \\ q^n_{t+1} = q^n_t, \eta^n_{t+1} = \eta^n_t, & \text{if } a^n_q = 0 \end{cases}$$

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

  ...

- Handset maker n_N observes all previous actions, draws i.i.d private cost shocks $\varepsilon^{n_N}_t$, 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

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

$a_{\mathcal{N}(n)}$ denotes the actions of firms that have moved before n. A key component of the model is the constraint that $q_t^n + a_q^n \leq q_{t+1}^Q$. I use this constraint to capture the complementarity of the upstream and downstream innovations. The Bellman equation of handset maker 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 $V_T = \dfrac{\pi\left(s_T\right)}{1-\beta}$.

The innovation cost is specified as

$$C^Q\left(a^Q, \varepsilon_t^Q\right)=\begin{cases}0, & a^Q=0\\ \exp\left(\gamma_0^Q+\gamma_1^Q a^Q+\sigma^Q\varepsilon_t^Q\right) & a^Q>0\end{cases} \tag{2}$$

$$C^n\left(a^n, \varepsilon_t^n\right)=\begin{cases}0, & a_q^n=0\\ \exp\left(\gamma_0^n+\gamma_1^n a_q^n-\gamma_2^n a_\eta^n+\sigma^n\varepsilon_t^q\right) & a_q^n>0\end{cases} \tag{3}$$

The cost shocks ε follow the standard normal distribution. I allow the innovation cost of a handset maker to depend on the increment of quality frontier and the choice of proportions of handsets using Qualcomm chipsets.

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. The two assumptions have also been used in Igami (2015) for similar purposes. I explore the robustness of both assumptions in Appendix D.

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), Hart and Moore (1990) and others have shown 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" in this model is the difficulty of communicating a firm's investment decisions to others before the realization of the investment. 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. As discussed in the Introduction, identifying and agreeing to the exact nature of innovation may be hard enough in the face of uncertain future demand and product designs. 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.

On the other hand, the ex post enforcement problems may be overcome in an infinite horizon dynamic game, where a PBE may exist such that firms condition strategies on past actions and Qualcomm may be able to credibly delay new chipset releases and "punish" HTC, if HTC does not pay Qualcomm a transfer or commit to Qualcomm chipsets after a Qualcomm innovation. The assumptions of a finite horizon and sequential moves in my model have the effect of a Markov refinement and eliminate the cooperative equilibria. Folk theorem suggests that upstream and downstream firms can play cooperatively when the discount factor β is sufficiently close to 1. A body of theoretical literature has examined such cooperative strategies and how the holdup problems manifest differently in a dynamic context (Halonen (2002), Baker et al. (2002), Che and Sákovics (2004) and Che and Sákovics (2007), to name a few).

One way to capture coordination in the structural model above is to specify the period profit of HTC as $\varsigma\pi^{Q} + \pi^{HTC}$, where $\varsigma \in (0, 1)$ is a reduced form cooperation parameter to be estimated from data. Identifying conduct parameters like ς requires excluded demand shifters (Bresnahan (1982) and Berry and Haile (2014)) or observed cost data. In Section 5.2, I discuss how cost data can provide information on ς.

4 Bargaining Model

This section describes a static model of bargaining that determines the profit function $\pi(s_t)$ used as input to the dynamic model. 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 and set wholesale prices.

I start with the demand function.

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 brand 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, chipset generation fixed effects, camera resolution, weight and battery talk time (the longest time that a single battery charge will last when a user constantly talks on the phone). μ_{jt} denotes the mean consumer utility, 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

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

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:

$$\omega_{jt} \equiv \underbrace{\lambda_q \exp\left(q_{jt}\right) + \lambda_{n(j)} + \lambda_{Q(j)} + \zeta_{c(j)t}}_{\substack{\text{quality, handset maker FE} \\ \text{use Qualcomm?} \\ \text{carrier-time FE}}} + \underbrace{\varkappa_{jt}}_{\text{shock}}. \tag{4}$$

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

$$\max_{p_{jt}, j \in \mathcal{J}_{nt}} \sum_{j \in \mathcal{J}_{nt}} \left(p_{jt} - \psi_{jt} - (\omega_{jt} - r_{jt})\right) D_{jt}, \tag{5}$$

and handset makers effectively choose retail prices. 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

$$p - \psi - \omega = (L * \Delta)^{-1} s, \tag{6}$$

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), $\Delta_{jj'}$ is the derivative of the demand for j' with respect to the price of j, and $*$ represents element-wise 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 given a set of products $\mathcal{J}_t$, I start with the prices of period t's products whose qualities are closest to those in $\mathcal{J}_t$, and apply (6) as a fixed point mapping to solve for the equilibrium prices. In practice, I find that this procedure always converges numerically. 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.[4] Qualcomm negotiates with each handset maker n separately. Denote the vector of chipset prices specific to a Qualcomm-n bargaining pair as $\boldsymbol{\psi}_{nt} = (\psi_{jt}, j \in \mathcal{J}_{Qt} \cap \mathcal{J}_{nt})$.

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

The chipset prices are set in a bargaining equilibrium:

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

$$\left[\pi_t^Q\left(\boldsymbol{\psi}_{nt}, \boldsymbol{\psi}_{-nt}\right) - \tilde{\pi}_t^Q\left(\boldsymbol{\psi}_{-nt}\right)\right]^{\tau_t} \cdot \left[\pi_t^n\left(\boldsymbol{\psi}_{nt}, \boldsymbol{\psi}_{-nt}\right) - \tilde{\pi}_t^n\left(\boldsymbol{\psi}_{-nt}\right)\right]^{1-\tau_t}, \tag{7}$$

where $\tilde{\pi}$ is the disagreement payoff, and τ_t is the bargaining weight.[5]

For $\tilde{\pi}$, I assume that when the negotiation breaks down, the handset maker n uses an alternative functionally identical chipsets at a price $\bar{\psi}$ for handsets in $\mathcal{J}_{Qt} \cap \mathcal{J}_{nt}$ and Qualcomm loses revenues from these handsets. Other chipset prices are held fixed and the downstream pricing equilibrium is recalculated. Realistically, the handset quality may also change if a non-Qualcomm chipset is used. I consider this possibility in a robustness check in Appendix D. Based on (7) and the definition of Nash bargaining equilibrium, the vector of all Qualcomm chipset prices ψ satisfies the following first order condition:

$$\psi = \underline{\psi} + \Theta^{-1}\Phi, \tag{8}$$

where Θ and Φ are defined (differently) for each bargaining model in Appendix A.[6]

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. The use of lump sum transfers would avoid double marginalization. The reality is likely somewhere between the two types of contracts: on one hand, firms have incentives to avoid contractual inefficiency; on the other hand, linear fees help to alleviate a moral hazard concern: one party can refuse to pay for future shipment if, for example, there is quality deficiency. As will be clear in Section 6, the double marginalization inefficiency due to the linear contract is small compared to firms' total profits.

4.4 Period Profit

Collect the number of products, product qualities, chipset origins 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, $\pi_t^Q\left(y, \xi, \varkappa, \tau\right)$ and $\pi_t^n\left(y, \xi, \varkappa, \tau\right)$. 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 $g\left(Y; \tilde{s}_t, \theta\right)$: the set of products is a random variable that has a stationary distribution conditional on the state variables defined in Section 3,[7] where $\tilde{s}_t$ is a vector of handset

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

[6] There may also be multiple bargaining equilibria. To define the period profit for each firm, I use (8) as a fixed point mapping to iteratively solve for the equilibrium chipset prices, starting from $1.2\underline{\psi}$.

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

maker quality frontiers and thus a subvector of the full state s_t in the dynamic model. The specification of $g(\cdot)$ relies on the empirical distribution of products and described in Appendix B. I further assume that Y, ξ, $\varkappa$ and τ_t are distributed independently. Firms use $\pi^Q(s_t) \equiv \pi^Q(\tilde{s}_t) \equiv E_{Y,\xi,\varkappa,\tau|\tilde{s}_t}\left(\pi_t^Q(Y,\xi,\varkappa,\tau)\right)$ and $\pi^n(s_t) \equiv \pi^n(\tilde{s}_t) \equiv E_{Y,\xi,\varkappa.\tau|\tilde{s}_t}(\pi_t^n(Y,\xi,\varkappa,\tau))$ to make dynamic innovation decisions.

There is an important practical advantage for using a static model. The assumptions of the static demand and pricing and the stationarity of the product set distribution allow the period profits to be computed separately from the dynamic game. The integration of $\pi_t^Q(Y,\xi,\varkappa,\tau)$ and $\pi_t^n(Y,\xi,\varkappa,\tau)$ over the distribution of products, demand shocks, cost shocks and bargaining weights 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 game. In reality, smartphones are both durable goods and network goods (Sinkinson (2014) and Luo (2016)). 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 assumes that the two effects are exogenous. The static model also rules out long term contracts. Qualcomm may offer handset makers higher discount to be used in more phones for several periods. This possibility is captured in the innovation cost parameter γ_2^n in (3). When γ_2^n is positive, the innovation cost decreases if n uses Qualcomm chipsets on more of its handsets. γ_2^n may reflects Qualcomm's willingness to help a more devoted handset makers to develop products in a more cost-efficient way, but γ_2^n may also represent monetary transfers to handset makers. The limitation is that the transfer is not an endogenous outcome but taken as a structural primitive. γ_2^n may change under an alternative market structure, but I do not find counterfactual simulation results sensitive to perturbations to the estimates.

5 Estimation

5.1 Demand and Smartphone Marginal Cost

I estimate demand using BLP instruments constructed with handset characteristics 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 Table 4. The characteristics x_j used to construct the quality index include the screen size,[8] 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 effects correspond with Snapdragon S1 through S4 and comparable products. The omitted generation is for phones that do not use chipsets or use chipsets older than Snapdragon S1. The brand fixed effects of Apple, Samsung and BlackBerry are also included. The demand estimates are reasonably intuitive, with higher generation, camera resolution, lower weights and longer battery

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

Table 4: Demand Side Estimates

		Est	Se
β	Screen Size (inch)	1	-
	Chipset Generation S1	0.460	0.113
	Chipset Generation S2	0.718	0.147
	Chipset Generation S3	1.055	0.200
	Chipset Generation S4	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 year FE, Quarter FE, Samsung, BlackBerry FE			

Table 5: Supply Side Estimates

		Est	Se
λ_q	exp (quality/10) ($)	359.251	3.641
λ_Q	Use Qualcomm? ($)	-21.858	0.301
Carrier year FE, Quarter FE, Apple, Samsung, BlackBerry FE			
		Range	Median
τ_t	Bargaining weight	[0.28, 0.78]	0.47
ψ_t	Chipset prices ($)	[28.71, 51.29]	35.91
Values inverted from the bargaining FOC (8)			

talk time contributing positively to the index. A one-hour increase in battery talk time is equivalent to a price decrease of 6.5 dollars for an average consumer. Similarly, a one-megapixel increase in camera resolution is equivalent to a price decrease of 10.9 dollars, while an increase in the screen size by 0.1 inches is equivalent to a price decrease of 11.7 dollars. Each chipset generation upgrade is equivalent to a price drop between 30 to 78 dollars. The estimated standard deviation of consumers' taste for quality is about 40% of the average taste, suggesting that consumers are heterogeneous in their willingness-to-pay for quality. In our estimation, we include Apple, BlackBerry and Samsung dummies and group all other brands as a baseline brand in the utility function. The Apple brand fixed effect in the demand function is large, worth over $400 to consumers. Additional details of the demand estimates are documented in Fan and Yang (2016).

I now discuss how to estimate the marginal cost function (4). The goal is to invert out the bargaining parameters τ_t and chipset prices ψ_t, and estimate ω as a function of handset characteristics. I fix Qualcomm's marginal cost of manufacturing a chipset to be $\underline{\psi} = \$20$, and the cost of non-Qualcomm chipsets at the disagreement point to be $\bar{\psi} = \$60$. I base the calibrated value of $\underline{\psi}$

based on conversations with fabrication plant engineers and analysts. $\bar{\psi}$ could be directly estimated if I observe in data that a handset maker uses different chipsets on the same handset. I do not observe such variations during my sample period. I choose a relatively large $\bar{\psi}$ to take into account not only the direct cost of buying the alternative chipset, but also potentially the additional cost of equipping a phone with a chipset which the phone was not designed to use. I show in robustness checks that further allowing the handset quality to decrease does not change the conclusion very much. The results later will show that even with a large $\bar{\psi}$, which is disadvantageous for handset makers, the potential harm of raising rivals' costs is still limited in the counterfactual vertical integration. Given the estimated demand function and observed prices, the full marginal cost $\omega + \psi$ can be inverted using the first order condition (6). To estimate the coefficients in (4), I need to break out the chipset prices ψ. To impute ψ, I rely on the average Qualcomm markup data in its quarterly financial reports and the equilibrium first order conditions (8) corresponding with the Nash product. For every value of τ_t, I can solve for a vector of chipset prices consistent with the observed retail prices using (8) in every t. If the solution is unique, then there exists a one-to-one relationship between τ_t 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 τ_t and the average Qualcomm markup. I use this relationship to compute a τ_t: the gross margin data are quarterly, and I invert out a τ_t for every quarter.[9] ψ for phones not using Qualcomm is set to 0. After τ and ψ are inverted out, I regress ω on handset qualities, carrier/year FE, quarter FE and brand fixed effects and whether the handset is designed to use Qualcomm chipsets.

Table 5 shows the supply side estimates. The non-chipset components' costs increase with the quality of the smartphone. Using a Qualcomm chipset saves \$22 in marginal cost for the non-chipset part of the phone. An alternative interpretation is that if a handset is designed to use a non-Qualcomm chipset, its chipset costs about \$22. I also present the range of inverted τ and ψ in Table 5. There are 17 τ's for each quarter in my sample. The median Qualcomm chipset price is about \$36.

One may be concerned that these supply side parameters are not "structural": in a counterfactual vertical integration between Qualcomm and a handset maker, entry into the chipset industry might be expected. First, the foreclosure effect may prompt handset makers to seek alternative suppliers. Secondly, because a handset maker may have to reveal proprietary phone designs to Qualcomm during a negotiation, an integrated Qualcomm would have an incentive to exploit this information for its own downstream subsidiary (Allain, Chambolle and Rey (2011)). Therefore additional chipset makers may enter to meet the increased demand for Qualcomm alternatives. In Appendix D, I consider a robustness test where handset makers face a smaller $\bar{\psi}$ in the counterfactual of vertical integration.

[9] I use a minimization algorithm to match the model predicted markup with data. I run the algorithm from 10 different starting points and always find a unique solution.

5.2 Sunk Cost of Innovation

The goal is to estimate parameters in (2) and (3). I first use demand estimates to construct handset quality frontiers and the profit functions $\pi^Q(s_t), \pi^n(s_t)$ defined in Section 4.4 as input to the dynamic game. 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 of products by n in t: $q_t^n = \max_j q_j, j \in \mathcal{J}_{nt}$. By the definition in Section 4.4, $\pi^Q(s_t) \equiv \pi^Q(\tilde{s}_t)$ and $\pi^n(s_t) \equiv \pi^n(\tilde{s}_t)$ can be simulated with demand estimates.

However, I do not directly observe the quality of Qualcomm chipsets or Qualcomm frontiers. I only observe the latest generation of Qualcomm chipsets according to the announcement dates. The chipset generation fixed effects in the quality index are not the qualities of Qualcomm chipsets. The Qualcomm quality frontier of generation g should be interpreted as the highest quality phone that a handset maker can produce with Qualcomm's generation g chipset. I argue that with appropriate assumptions on the bounds of Qualcomm qualities, one can still make inferences about the underlying cost primitives. First, handset qualities are informative about Qualcomm qualities. Other than vertically integrated Apple, Qualcomm quality is at least as high as the frontiers of other handset makers. Therefore the maximum of non-Apple handset maker frontiers, $\max_{n\neq Apple} q_t^n$ forms the lower bound of Qualcomm quality frontier in t. To bound Qualcomm quality frontier from above, I make the following assumption:

Assumption 1. *When Qualcomm's latest chipset generation is g in period t, Qualcomm quality q_t^Q is less than the quality of the first non-Apple handset using generation $g+1$ Qualcomm chipset.*

For example, Qualcomm's latest generation is S3 in November 2011, and in my data set, the first phone that uses the next generation S4 chipsets is One S by HTC (available in March 2012) with quality index 6.88. Therefore under the assumption above, Qualcomm quality in November 2011 is less than 6.88, and no non-Apple handset maker can produce a phone with quality higher than 6.88 until S4 becomes available. In data, Qualcomm added new varieties of chipsets to the Snapdragon S3 product line that enabled some handset makers to produce phones whose qualities are higher than 6.88. Qualcomm only added these chipsets after the launch of Snapdragon S4 and the assumption above is still valid.

I use a Simulated Minimum Distance estimator with one inequality constraint to recover a confidence set for the innovation cost parameters. For any vector of innovation cost parameters, I am able to solve for the unique Perfect Bayesian Equilibrium for a discount rate of 0.99. To limit the computational burden, I estimate a dynamic game of Qualcomm and the top three handset makers from 2010 to 2013: Apple, Samsung and HTC. In Section 7, I include BlackBerry, Motorola and LG but assume that their quality frontiers are exogenous conditional on HTC's quality frontier. When solving the dynamic game, I assume that the order of moves is Qualcomm, Apple, Samsung and HTC. Appendix D considers the case where the order of handset maker moves is reversed. Consistent with data, Apple is assumed to always use non-Qualcomm chipsets $\left(\eta^A = 0\right)$ 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. To guard against the effect of the finite horizon assumption, the model is solved by backward induction from six months after the last period of the data, September 2013. In Appendix D, I further check the sensitivity of the finite horizon assumptions by solving the game from March 2014. The carrier-time fixed effects of April 2013 to March 2014 are extrapolated from demand estimates in earlier periods. To accommodate the potential heterogeneity in the sunk cost functions (2) and (3), I estimate a firm specific γ_0 and γ_1. I restrict $\sigma^{handset}\equiv\sigma^{Apple}=\sigma^{Samsung}=\sigma^{HTC}$ and estimate a different $\sigma^{Qualcomm}$, giving me a total of 11 parameters to estimate. There are a total of 51 months of data. I fix the qualities in month 1 and use quality choices of the next $T=50$ periods for estimation. To address the research question, I focus on making the model replicate the total amount of quality increase and Qualcomm chipset usage on average. Like Goettler and Gordon (2011), I match stationary equality moments in simulation and data:

1. mean innovation rates, defined as $\bar{\imath}=\left(q_{51}-q_1\right)/T$ for Apple, Samsung and HTC;
2. mean proportion of Qualcomm chipsets on Samsung products, $\sum_{t=2}^{51}\eta_t/T$.

Denote the upper bound of Qualcomm quality in each period as ρ_t. Use $q_{t,r}^{\cdot}$ and R to denote the quality in simulation r and the total number of simulations. The stationary inequality moment based on Assumption 1 is:

1. $\sum_{r=1}^{R}\sum_{t=2}^{51}\left(q_{t,r}^{Q}-\max\left(q_{t,r}^{Sam},q_{t,r}^{HTC}\right)\right)/RT\leq\sum_{t=2}^{51}\left(\rho_t^{Q}-\max\left(q_t^{Sam},q_t^{HTC}\right)\right)/T.$

Denote the equality moments as g^e and inequality moments as $g^{ie}\leq 0$. The 95% confidence set of the identified set in Shi and Shum (2015) is defined as

$$CS_T=\left\{\theta\in\Theta\,:\,g^{ie}\leq 0,g^{e\prime}Wg^e\leq\chi_4^2\left(0.95\right)/T\right\},\tag{9}$$

where W is the weighting matrix and $\chi_4^2\left(0.95\right)$ is the 95% quantile of χ^2 distribution of 4 degrees of freedom. I detail the model solution, estimation and simulation procedure in Appendix C.

There are 5 moments for 11 parameters. I leave the model under-identified for two reasons. First, these moments are closely related to the identification of the mean innovation costs. For example, high handset maker γ_0 or γ_1 will imply slow innovation and cause deviations in the first set of equality moments. High Qualcomm γ_0 or γ_1 will also imply slow Qualcomm innovation, which also slows down Samsung and HTC innovation. If Qualcomm γ_0 or γ_1 are low, Qualcomm innovates more quickly and will violate the inequality constraint. The Qualcomm usage parameter γ_2^n is identified by the second equality moment. Secondly, the functional form restriction and the dynamic equilibrium strategies imply a tight relationship between the four firms' innovation rates as well as a tight relationship between the innovation rates and other features of the innovation paths, such as the variance of the innovation rates. Adding additional moments rejects the current

Table 6: Estimates of Innovation Costs

		95% Confidence Set
γ_0	Apple	[0.36, 0.84]
	Samsung	[-0.83, 1.05]
	HTC	[-0.36, 0.61]
	Qualcomm	[-4.86, -4.64]
γ_1	Apple	[16.02, 17.52]
	Samsung	[8.08, 13.18]
	HTC	[8.38, 10.40]
	Qualcomm	[6.03, 7.17]
γ_2	Samsung	[4.10, 5.12]
σ	Handset	[4.13, 5.08]
	Qualcomm	[0.34, 0.61]

I report the min and max of each parameter in the confidence set. The confidence set consists of a set of vectors of parameters that satisfy (9) and is not a Cartesian product of the intervals above.

model, while a more flexible functional form of the innovation cost function would add to the high computational cost of a simulation-based estimator. Moment inequality methods that allow for model mis-specification (Chernozhukov et al. (2007)) and other alternatives (Andrews and Soares (2010) and Romano et al. (2014), for example) involve a bootstrap step to compute the confidence set and are also not computationally feasible. Balancing the computational feasibility and model flexibility, I choose the former, focusing on matching the moments most important to the research question and taking advantage of the computationally simple set estimator in Shi and Shum (2015).

The estimated 95% confidence set consists of a set of vectors of parameters that satisfy 9. I report the minimum and maximum of each parameter in the confidence set in Table 6. Because the cost functions are specified as an exponential function of a linear combination of quality increases, we can interpret the parameter estimates as a "semi-elasticity". For example, increasing quality by 0.1 unit increases the innovation cost by 1.6 to 1.7 times for Apple. Using Qualcomm chipsets for all handsets reduces the innovation sunk costs for Samsung. The magnitude of the handset maker private shock is large.

I use simulation to interpret the estimates in terms of the levels of innovation costs. I use a procedure described in Appendix C to sample a representative set of points from the confidence set to simulate the dynamic model. The model is simulated at these parameter values for 960 times for the sample period. The simulated total investment expenditures of Apple, Samsung, HTC and Qualcomm across sampled points in the confidence set are reported in Table 7. To examine whether these figures are sensible, I sum up the operating expenses (R&D, selling, general and administrative costs but not manufacturing costs of the goods sold, in the accounting sense) in HTC's financial reports, discounted by an annual rate of $0.99^{12} = 0.89$. Apple, Samsung and

Table 7: Simulated Investment Range ($ Billion), Jan 2009 to March 2013

	Investment
Apple	[6.72, 7.74]
Samsung	[1.84, 3.31]
HTC	[3.07, 4.75]
Qualcomm	[0.61, 0.86]

Qualcomm have major operations outside the application chipset and smartphone industries, and their accounting costs are less relevant. The discounted HTC operating expenses are $6.83 billion dollars during the period. According to HTC's annual reports, 51% of HTC revenues come from North America. Under the assumptions that the US market accounts for a constant share of the world market and the US market accounts for the majority of HTC's North American revenues, the total simulated HTC investment will be at least as high as the range of 6.14 to 9.50 billion dollars. The simulated investment level matches HTC accounting figures in scale.

One may also view the comparison as evidence for a model of incomplete contracts. As discussed in Section 3, to allow for cooperative strategies, I can specify HTC period profit as $\varsigma\pi^{Q} + \pi^{HTC}$ and estimate ς. Cost data can be informative about ς. If cooperation increases innovation and hence total investment, then innovation rates and investment levels are higher when $\varsigma = 1$ than when $\varsigma = 0$. If the quality choice data are generated by a model of $\varsigma = 1$, my estimates under the assumption that $\varsigma = 0$ would incorrectly attribute the high levels of innovation to low innovation costs instead of cooperation, and the simulated HTC innovation costs would be lower than the actual investment. In the above, I find that HTC investment in financial reports does not appear to be higher than the simulated innovation costs.

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, resemble typical downstream competitors to a vertically integrated firm. Samsung may decrease the use of Qualcomm chipsets because of the raising rivals' cost effect, but could also increase the use of Qualcomm chipsets to reduce innovation costs. I simulate the effects of vertical integration and decompose the effects into the investment effects and price effects. I simulate the baseline and every counterfactual scenario 240 times for the period of January 2009 to December 2011 at points sampled from the confidence set as described in Appendix C. All dollar figures are discounted to January 2009.

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 firms also jointly set prices, reducing double marginalization but potentially raising rivals' costs. With the first effect, the new dynamic programming problem for Qualcomm and HTC becomes

$$\begin{aligned} \max_{a^Q} \left\{ -C^Q\left(a^Q, \varepsilon^Q\right) + \beta E\left(V_{t+1}^{VI}\left(s_{t+1}\right) \middle| a^Q, s_t\right)\right\} \\ \max_{a^{HTC}} \left\{ -C^{HTC}\left(a^{HTC}, \varepsilon^{HTC}\right) + \beta E\left(V_{t+1}^{VI}\left(s_{t+1}\right) \middle| a^Q, a_{\mathcal{N}(HTC)}, s_t\right)\right\}, \end{aligned} \tag{10}$$

and the Bellman equation for the joint firm is

$$V_t^{VI}\left(s_t\right) = \tilde{\pi}^{VI} + E\left(-C^Q\left(a^{Q\star}, \varepsilon^Q\right) - C^{HTC}\left(a^{HTC\star}, \varepsilon^{HTC}\right) + \beta V_{t+1}^{VI}\left(s_{t+1}\right) | s_t\right), \tag{11}$$

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

I conduct three sets of simulations: no VI, investment coordination only and full vertical integration with both investment and price effects. The purpose of the second simulation is to parse out the investment 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. the investment decisions of Qualcomm and HTC are solutions to (10), but I replace $\tilde{\pi}^{VI} = \tilde{\pi}^Q + \tilde{\pi}^{HTC}$ with $\pi^Q + \pi^{HTC}$ in (11). The difference between this simulation and the baseline simulation shows the net investment effects, while the difference between this simulation and the full vertical integration simulation shows the additional price effects.

Table 8 reports the simulation results. The end points of the intervals are the maximum and minimum of the simulations across points sampled from the confidence set. I first summarize the main findings:

1. Vertical integration increases the innovation of both upstream and downstream firms; the changes in Apple's innovation rates are comparatively much smaller.

2. Consumer surplus and total surplus increase.

3. The investment effects on the innovation rates of Qualcomm, HTC and Samsung and the surpluses are larger than the price effects.

4. Price effects decrease HTC's retail prices and increase the prices of Qualcomm chipsets sold to Samsung.

Next, I discuss the intuition behind these observations using the main specification in Table 8. The column "No VI" reports the range of simulation results at the observed market structure and parameters sampled from the confidence set according to the procedure in Appendix C, and the column "Investment Coordination" reports the results where Qualcomm and HTC coordinate investment but not pricing. The column "Full VI" reports the results when Qualcomm and HTC coordinate both investment and pricing. The numbers under "Difference %" represent the changes in results under different market structure but at the same vector of parameters. I calculate the percentage changes for all parameters in the sampled set of parameters and report the minimum and maximum.

The increase of Qualcomm and HTC innovation is intuitive, as they internalize the marginal value of innovation on each other. To visualize the magnitude of the effect, I examine the first order difference at a vector of parameters in the confidence set, $V(q+\delta) - V(q)$, 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 $\frac{\partial V^{HTC}}{\partial q^{HTC}}$ of January 2011 in Fig. 2, where Apple and Samsung quality levels (brand fixed effect adjusted) are fixed at 8.2 (iPhone 3GS) and 6.7 (Galaxy S II). Per unit increase of Qualcomm or HTC quality, HTC value function would increase in the range of 0.4 to 1.2 billion dollars. Per unit increase of HTC quality increases Qualcomm value function by 0.05 to over 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. While the average number of months that $q^{Samsung} = q^Q$ is only reduced from 4.78 months to 4.50 months, I argue that the harm of being constrained by Qualcomm is much lessened. To show this, I examine the second order difference of Samsung's value function, denoted as $\frac{\partial^2 V^{Samsung}}{\partial q^Q \partial q^{Samsung}}$. I normalize Samsung's marginal value of innovation to 0 when Samsung is constrained. If it is profitable for Samsung to innovate while being constrained, Samsung's marginal value of innovation should increase sharply (from 0) when Samsung becomes unconstrained. In this case, $\frac{\partial^2 V^{Samsung}}{\partial q^Q \partial q^{Samsung}}$ should be positive, and a larger value implies greater harm from the constraint, because Samsung likely has to delay a profitable innovations. In Fig. 3, I plot the second order difference when Apple and HTC qualities (brand fixed effect adjusted) are fixed at 9 and 6. At the baseline, the second order derivative is indeed positive and large when the distance to Qualcomm frontier increases from 0, suggesting that Samsung is likely to miss profitable innovation opportunities when constrained. The value of the innovation that Samsung fails to capture because of the constraint is economically large: the spike in the left figure accounts for 20 to 40% of the corresponding marginal value of Samsung innovation. In the VI counterfactual, the magnitude of the second order difference is smaller. The results show that the net investment effect of vertical integration on Samsung, which includes the effect from the lessened constraint and the competitive effect, is positive. Samsung also uses more Qualcomm chipsets, reducing the innovation costs.

Furthermore, vertical integration increases consumer and producer surplus. Most of the increase come from the faster innovation, but the decrease in HTC prices also helps to increase consumer surplus in the main specification. In particular, while higher quality products may be priced higher, eliminating double marginalization reduces HTC retail prices by about 6% even when price effects increase HTC innovation. Qualcomm increases the prices of the chipsets sold to Samsung, but the subsequent changes in Samsung's retail prices are smaller.

Figure 2: Marginal Effects of Qualities on HTC and Qualcomm Value Functions

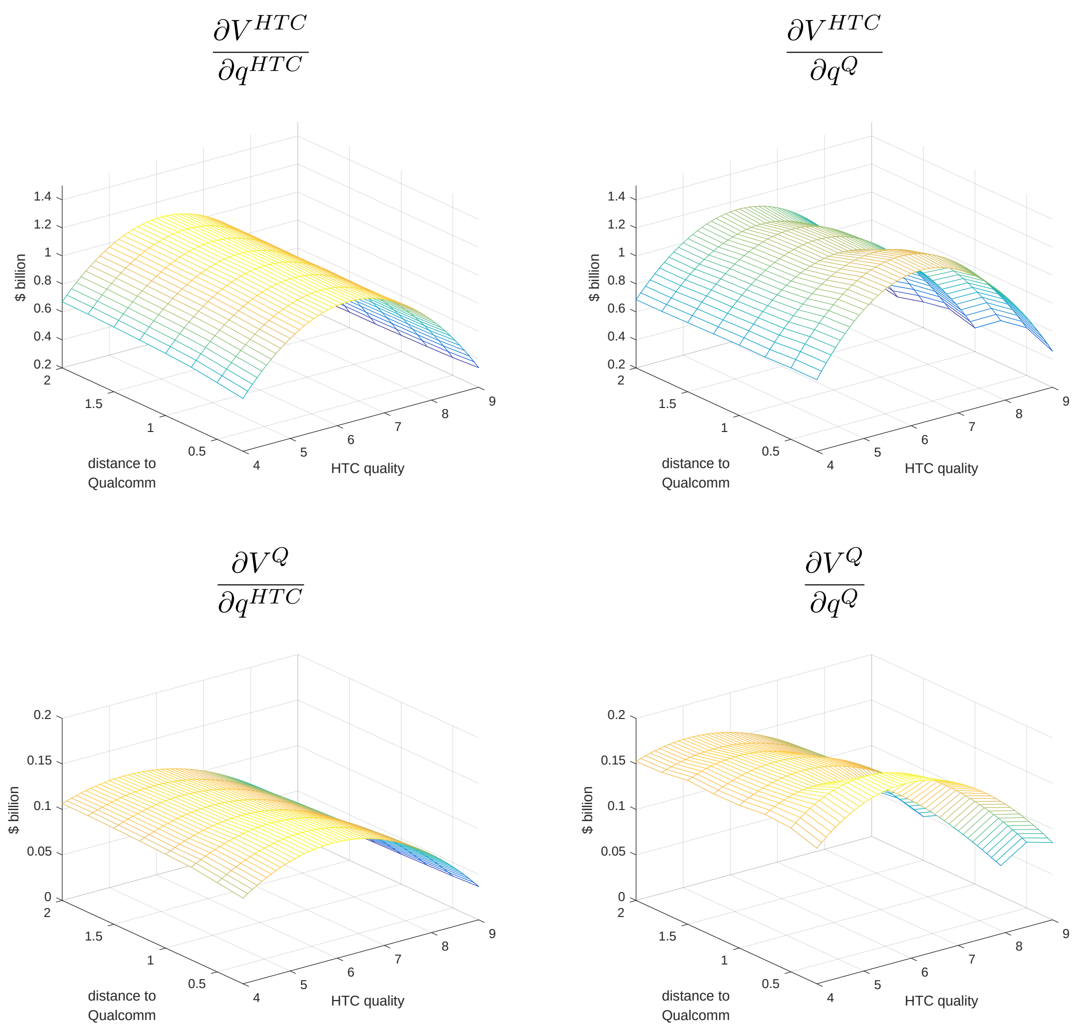
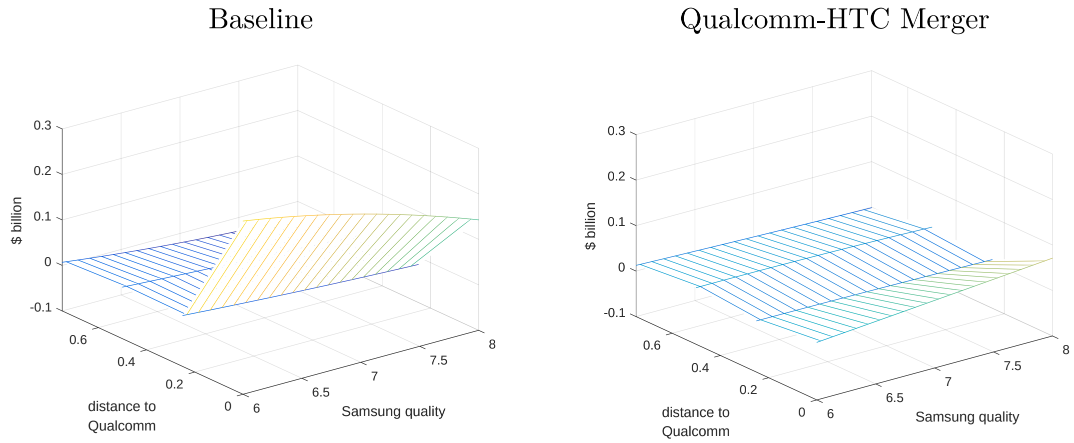


Figure 3: Marginal Effect of Qualcomm Quality on the Marginal Value of Samsung Innovation



7 Robustness Analysis

I consider two main robustness checks in this section. The first check considers the effect of additional handset makers $\tilde{\mathcal{N}} = \{\text{BlackBerry, Motorola, LG}\}$. The second check considers Qualcomm's royalty income. Additional robustness checks are available in Appendix D.

In the first robustness check, I assume that quality frontiers of firms in $\tilde{\mathcal{N}}$ are exogenous conditional on the HTC frontier. Given $\tilde{s}_t = \left(q_t^{Apple}, q_t^{Samsung}, q_t^{HTC}\right)$, I compute a firm's profit function as

$$E_{q_t^k, k\in\tilde{\mathcal{N}}|\tilde{s}_t}\left(\pi_t\left(\tilde{s}_t, \left(q_t^k\right)_{k\in\tilde{\mathcal{N}}}\right)\right), \tag{12}$$

where both the frontiers and associated sets of products by $k \in \tilde{\mathcal{N}}$ are random variables to be integrated out. The procedure is described in Appendix B.

I also consider the effect that Qualcomm collects patent royalties from handset makers. To model the effect of royalty fees, I first construct a measure of wholesale prices. I collect additional data on the average service prices consumers pay to carriers. Consumers during the sample period are typically on two-year contracts, and I use the retail phone price p_j plus the discounted sum of consumer service payments v_t as the total carrier revenue per customer. The average of v_t in my calculation is 855 dollars. A wireless carrier whose main businesses are wireless and data services (like T-Mobile) typically have a gross margin of 50% according to their financial reports. Assuming that the wholesale prices of the phones are the only marginal costs carriers face, I measure the wholesale price as $w_{jt} = \frac{1}{2}(p_{jt} + v_t)$. Given the royalty rate z_n for handset maker n, the handset maker profit function becomes

$$\max_{p_{jt}, j\in\mathcal{J}_{nt}} \sum_{j\in\mathcal{J}_{nt}} \left((1-z_n)\cdot\frac{1}{2}(p_j + v_t) - \psi_{jt} - \omega_{jt}\right) D_{jt},$$

and Qualcomm profit function is modified to include the additional revenues from royalties. At the disagreement point in the bargaining game, Qualcomm continues to earn royalties from the handset maker even if the handset maker switches to an alternative chipset. I assume that Apple's royalty rate is 2%, Samsung 3% and HTC 5% (Arghire (2009),Clark (2009)).

The estimates of the two robustness checks are reported in Table 9. The simulation results are reported in Table 10 and 11. The producer surplus for the first robustness check includes the variable profits of firms in $\tilde{\mathcal{N}}$, also calculated by (12). The estimates of the first robustness check are similar to the main specification. The estimated γ_1 for Qualcomm in the second robustness check is much larger. In the counterfactual simulation, the qualitative patterns of both specifications are broadly consistent with the main specification. The counterfactual innovation rates increase less in the first robustness check.

Qualcomm chipsets are bundled with modems, but Qualcomm also sells standalone modems to handset makers, including Apple. Qualcomm thus internalizes some of the value of Apple innovations, and modem sales affect Qualcomm innovations in a way similar to Qualcomm royalty revenues. In fact, Mock (2005) documents instances where Qualcomm collects only royalties from some clients and sells them modems for free. Because there are no detailed data on the modem manufacturers for phones in my sample, I did not conduct analysis regarding modem sales.

8 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 investment effects. The results suggest that the dynamic effect of vertical integration may be large and positive, providing support for giving more weight to this factor 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[10] would imply different estimates of firm profits, but I do not expect the bias to reverse the result: the investment effects are an order of magnitude larger than the price effects in the main specification. 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 bias the estimates of the innovation costs. However, including such

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

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 small compared with the investment effects.

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Table 8: Counterfactual Results: Main Specification, Jan 2009 to Dec 2011

		No VI	Investment Coordination	Full VI
Innovation Rate: $(q_{36} - q_1)/35$	Apple	[0.0403, 0.0444]	[0.0414, 0.0456]	[0.0414, 0.0454]
	Samsung	[0.1073, 0.1176]	[0.1282, 0.1305]	[0.1294, 0.1318]
	HTC	[0.0783, 0.0828]	[0.0933, 0.0951]	[0.0939, 0.0955]
	Qualcomm	[0.0731, 0.0863]	[0.0972, 0.0986]	[0.0979, 0.0999]
			Difference %	
	Apple		[1.65%, 2.73%]	[-0.38%, 0.00%]
	Samsung		[9.00%, 21.60%]	[0.47%, 1.00%]
	HTC		[14.13%, 19.27%]	[0.12%, 0.71%]
	Qualcomm		[12.68%, 34.93%]	[0.68%, 1.35%]
Consumer Surplus ($ Billion)		[22.8098, 23.5128]	[24.3182, 24.6586]	[24.6426, 24.9367]
			Difference %	
			[3.52%, 6.61%]	[1.02%, 1.33%]
CS+PS ($ Billion)		[47.3067, 48.5485]	[49.8703, 50.5868]	[50.2159, 50.8546]
			Difference %	
			[2.99%, 5.42%]	[0.44%, 0.69%]
Investment ($ Billion)	Apple	[5.0010, 5.7514]	[5.4768, 6.1684]	[5.4438, 6.1684]
	Samsung	[1.9861, 2.5103]	[2.3619, 2.8610]	[2.3818, 2.8867]
	HTC	[2.8243, 3.3867]	[5.0169, 5.1862]	[5.1319, 5.2378]
	Qualcomm	[0.5649, 0.6458]	[0.8673, 0.9249]	[0.8757, 0.9370]
			Difference %	
	Apple		[4.90%, 10.64%]	[-1.42%, 0.00%]
	Samsung		[13.97%, 20.24%]	[0.30%, 0.90%]
	HTC		[52.52%, 77.80%]	[0.33%, 2.29%]
	Qualcomm		[36.16%, 63.73%]	[0.96%, 1.33%]
Producer Surplus ($ Billion)	Apple	[16.2596, 16.7123]	[16.0346, 16.5620]	[15.9860, 16.4977]
	Samsung	[5.3042, 5.5648]	[5.7950, 6.1004]	[5.8327, 6.1299]
	HTC+Qualcomm	[2.8294, 2.9857]	[3.3428, 3.4171]	[3.3946, 3.4574]
			Difference %	
	Apple		[-1.38%, -0.14%]	[-0.41%, -0.25%]
	Samsung		[4.14%, 15.01%]	[-0.19%, 0.68%]
	HTC+Qualcomm		[13.99%, 18.38%]	[0.86%, 1.55%]
Retail Price ($)	Apple	[160.2546, 164.0366]	[160.0248, 164.2321]	[159.8585, 163.9179]
	Samsung	[224.9629, 231.3038]	[239.6018, 245.4518]	[241.4173, 247.1854]
	HTC	[198.1648, 202.4500]	[212.1613, 213.7752]	[199.4719, 200.7462]
			Difference %	
	Apple		[-0.26%, 0.39%]	[-0.19%, -0.09%]
	Samsung		[3.59%, 9.11%]	[0.31%, 0.76%]
	HTC		[5.43%, 7.22%]	[-6.24%, -5.98%]
Chipset Price ($)	Samsung	[31.3554, 31.3706]	[31.4121, 31.4150]	[32.4944, 32.5180]
	HTC	[31.3886, 31.3990]	[31.4238, 31.4278]	-
			Difference %	
	Samsung		[0.14%, 0.19%]	[3.44%, 3.51%]
	HTC		[0.09%, 0.11%]	-
Proportion of Samsung Using Qualcomm		[0.4473, 0.4895]	[0.5651, 0.5889]	[0.5679, 0.5908]
			Difference %	
			[20.30%, 28.24%]	[-0.10%, 0.71%]

Table 9: Estimates of Innovation Costs

		95% Confidence Set	
		Additional Handset Makers	With Royalties
γ_0	Apple	[0.06, 0.14]	[-0.34, 0.65]
	Samsung	[1.33, 1.52]	[-2.54, 0.01]
	HTC	[-0.12, 0.07]	[-0.61, 0.14]
	Qualcomm	[-4.15, -3.07]	[-4.89, -3.58]
γ_1	Apple	[20.46, 20.96]	[21.65, 25.71]
	Samsung	[3.49, 4.49]	[7.32, 13.08]
	HTC	[10.03, 10.03]	[10.61, 15.87]
	Qualcomm	[4.27, 7.80]	[14.57, 20.20]
γ_2	Samsung	[4.52, 4.71]	[4.86, 5.76]
σ	Handset	[5.09, 5.77]	[5.39, 6.92]
	Qualcomm	[1.84, 2.52]	[0.97, 3.08]

I report the min and max of each parameter in the confidence set.
The confidence set consists of a set of vectors of parameters
that satisfy (9) and is not a Cartesian product of the intervals above.

Table 10: Counterfactual Results: Additional Handset Makers, Jan 2009 to Dec 2011

		No VI	Investment Coordination	Full VI
Innovation Rate: $(q_{36} - q_1)/35$	Apple	[0.0359, 0.0372]	[0.0364, 0.0375]	[0.0363, 0.0374]
	Samsung	[0.0979, 0.1064]	[0.1072, 0.1147]	[0.1076, 0.1152]
	HTC	[0.0666, 0.0674]	[0.0685, 0.0704]	[0.0686, 0.0705]
	Qualcomm	[0.0638, 0.0737]	[0.0742, 0.0828]	[0.0747, 0.0831]
			Difference %	
	Apple		[0.78%, 1.37%]	[-0.32%, -0.08%]
	Samsung		[7.80%, 9.55%]	[0.35%, 0.51%]
	HTC		[2.06%, 5.69%]	[0.00%, 0.16%]
	Qualcomm		[12.33%, 16.23%]	[0.42%, 0.76%]
Consumer Surplus ($ Billion)		[29.1741, 29.8368]	[29.7669, 30.4251]	[29.9440, 30.6030]
			Difference %	
			[1.97%, 2.31%]	[0.58%, 0.62%]
CS+PS ($ Billion)		[56.5889, 57.5216]	[57.4451, 58.3713]	[57.5912, 58.5211]
			Difference %	
			[1.48%, 1.76%]	[0.25%, 0.27%]

Table 11: Counterfactual Results: Royalty Fees, Jan 2009 to Dec 2011

		No VI	Investment Coordination	Full VI
Innovation Rate: $(q_{36}-q_1)/35$	Apple	[0.0359, 0.0420]	[0.0372, 0.0435]	[0.0370, 0.0434]
	Samsung	[0.0975, 0.1159]	[0.1144, 0.1364]	[0.1155, 0.1384]
	HTC	[0.0712, 0.0910]	[0.0898, 0.1059]	[0.0909, 0.1064]
	Qualcomm	[0.0597, 0.0792]	[0.0778, 0.1014]	[0.0789, 0.1034]
			Difference %	
	Apple		[2.02%, 3.87%]	[-0.81%, -0.27%]
	Samsung		[15.02%, 21.73%]	[0.62%, 1.48%]
	HTC		[15.05%, 26.08%]	[0.24%, 1.22%]
	Qualcomm		[25.64%, 36.83%]	[0.88%, 1.94%]
Consumer Surplus ($ Billion)		[22.1926, 24.1541]	[23.6418, 25.8975]	[24.4723, 26.8162]
			Difference %	
			[6.35%, 8.06%]	[3.44%, 3.72%]
CS+PS ($ Billion)		[52.1515, 56.1937]	[55.1097, 59.5594]	[56.1202, 60.6983]
			Difference %	
			[5.29%, 6.71%]	[1.82%, 1.91%]

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

$$\tilde{\pi}^n = \sum_{j\in\mathcal{J}_n\cap\mathcal{J}_Q}\left(\tilde{p}_j-\omega_j-\bar{\psi}\right)\tilde{D}_j+\sum_{j\in\mathcal{J}_n\setminus\mathcal{J}_Q}\left(\tilde{p}_j-\omega_j\right)\tilde{D}_j,$$

and Qualcomm's disagreement profit is

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

where $\tilde{}$ 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

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

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 $\tilde{\boldsymbol{D}}_Q(n)$ 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

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

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

where $\tilde{\pi}^{\breve{n}}(n)$ corresponds with $\breve{n}$'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

In the specification that includes just Apple, HTC and Samsung, I sample from the empirical distribution of product sets in data to compute the expected profits. Specifically, given frontier q^n for n =Apple or HTC, I uniformly sample one period of n's products across all periods. If the highest quality $\tilde{q}_t^n$ of the sampled period is not q^n, I adjust the quality q_j of every product in the set to $q_j - \tilde{q}_t^n + q^n$. Given frontier q^{Sam} and $\eta \in \{0.3, 0.5, 0.7\}$, I sample one period of Samsung's products among the periods where the actual proportion using Qualcomm is closer to η than the other possible values of η. Using the set of products, demand and marginal cost estimates and the empirical distribution of shocks as well as bargaining weights, I simulate 50 sets of products for the given handset maker quality frontiers and use the average firm profits as π in the dynamic game.

In the specification that includes $\tilde{\mathcal{N}} = \{\text{BlackBerry, Motorla, LG}\}$, I sample from the empirical distribution of product sets of $n \in \tilde{\mathcal{N}}$ conditional on HTC frontier. Specifically, given frontier q^{HTC}, I sample a period of n's products uniformly from 5 months where HTC quality frontiers are closest to q^{HTC}. The expected profit is similarly calculated with 50 draws of sets of products.

C Solving, Estimating and Simulating the Dynamic Model

I set the quality increment for Qualcomm to be $\Delta = 0.25$, and $a^Q \in \{0, \mathit{\Delta}, 2\mathit{\Delta}, \dots, 6\mathit{\Delta}\}$. The handset makers' quality increment is $\delta = 0.25$, with $a_q^n \in \{0, \delta, 2\delta, 3\delta\}$ and $a_\eta^{Samsung} \in \{30\%, 50\%, 70\%\}$. 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 $t = 1, \dots, T$, $\eta \in \{30\%, 50\%, 70\%\}$, and $\delta^Q \in \{0, \delta, \dots, 10\delta\}$. I solve the value functions at the zeros of the Chebyshev polynomials and interpolate the value functions at other states. The choice probabilities of each firm are simulated with 200 draws of investment cost shocks.

To construct the confidence set in (9), I use a genetic algorithm that searches through an 11-dimensional space with a wide initial range. Each generation of the genetic algorithm iteration has 32 seeds, and I iterate over 96 generations. The intermediate functional values are saved and included in the confidence set if the corresponding $g^{e\prime} W g^e$ is below the critical value. I eventually obtain 300 to 600 points in the confidence set for every specification.

Because the moments I choose are stationary in nature, I use bootstrap to calculate the weighting matrix from data. I block bootstrap consecutive 12-month periods and compute the co-variance matrix of the equality moments. W is the inverse of this co-variance matrix.

Qualcomm quality is an unobserved state variable. To deal with the initial value problem, I calibrate the starting value of Qualcomm state and conduct robustness checks. The main specification starts the simulation that Qualcomm is 0.25 below the bound in period 1. The robustness checks in Appendix (D) considers two different starting states for Qualcomm.

Because Qualcomm bounds are based on the quality of handsets using the next generation's chipsets, and the last generation is S4 in data, there is also a "terminal value problem" that there are no quality measures in data to bound Qualcomm quality when it is in generation S4. The first handset using the next generation Qualcomm chipset Snapdragon 600 is Galaxy S4. To construct the quality index for such a phone, I need to calibrate the chipset generation fixed effect. I choose 2.474 for the chipset effect, which is 0.8 larger than the S4 chipset generation effect in demand estimates. The incremental increase in the chipset effect in previous generations is less than 0.63. In choosing a large chipset fixed effect and hence a high upper bound for Qualcomm, I err on the side of understating the benefit of vertical integration and yet still find sizable gains due to the vertical integration.

I use a randomly selected set of points in the confidence set to conduct counterfactual simulations. The purpose of the random sampling is to obtain a representative set of parameters from the confidence set. Specifically, I first find the centroid of the confidence set given the distance measure $\|\cdot\|_1$. Next, I classify all points in the confidence set into 5 groups based on the point's distance to the centroid. Denote the furthest distance as ℓ, group n consists of points whose distance to the centroid is between $\frac{n-1}{5}\ell$ and $\frac{n}{5}\ell$, inclusive of $\frac{n}{5}\ell$. I then randomly sample 2 points from each group and simulate each counterfactual analysis with a total of 10 points in the confidence set. Increasing the number of sampled points does not change the result in the main specification.

D Additional Robustness Checks

I conduct three types of robustness checks in this section. First, I re-estimate the static and/or the dynamic model and compute counterfactuals for 7 different deviations to the assumptions in the main text. Secondly, I examine to what extent the model can rationalize the data when the dynamic incentives are significantly weakened, by estimating the dynamic model when the discount rate is set to be 0.5. Lastly, I increase the attractiveness of the alternative chipset by decreasing $\bar{\psi}$ and compute the vertical integration counterfactual.

The 7 deviations to the assumptions in the main text are as follows:

1. Potential quality change at the disagreement point. I further allow the handset quality to decrease by 0.3 at the disagreement point.

2. The gross margin may overstate the actual Qualcomm chipset markup. I use 0.9×observed margin to estimate the chipset pricing model.

3. The gross margin may understate the actual Qualcomm chipset markup. I use 1.1×observed margin to estimate the chipset pricing model.

Table 12: Estimates of Innovation Costs : 95% Confidence Set

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	$\beta = 0.5$
γ_0	Apple	[-0.25, 0.16]	[-0.34, 0.92]	[-0.23, 0.53]	[-0.43, -0.11]	[-0.50, -0.41]	[0.53, 0.71]	[-0.07, 1.25]	[-0.67, 0.98]
	Samsung	[-0.10, 0.67]	[0.94, 1.19]	[0.14, 0.89]	[0.22, 1.52]	[0.32, 1.83]	[0.11, 1.95]	[0.02, 0.55]	[-0.43, -0.18]
	HTC	[-1.06, -0.06]	[-0.94, 0.31]	[-0.59, 0.19]	[-2.01, 0.39]	[-0.13, 0.50]	[-0.29, 0.89]	[0.18, 1.85]	[-0.38, -0.01]
	Qualcomm	[-3.95, -2.95]	[-4.10, -3.80]	[-4.21, -3.85]	[-3.76, -2.31]	[-3.97, -3.72]	[-3.91, -3.15]	[-3.94, -3.66]	[-2.89, -2.89]
γ_1	Apple	[20.13, 22.11]	[19.04, 22.84]	[19.88, 23.17]	[19.24, 20.25]	[25.27, 26.74]	[27.88, 29.13]	[21.92, 27.68]	[29.92, 34.11]
	Samsung	[10.47, 11.44]	[8.01, 12.01]	[8.70, 11.19]	[6.28, 8.27]	[10.60, 11.21]	[10.18, 15.87]	[10.71, 15.71]	[15.07, 15.07]
	HTC	[10.69, 13.00]	[9.59, 13.59]	[10.08, 12.87]	[9.61, 12.27]	[11.63, 12.51]	[11.10, 12.10]	[9.40, 12.83]	[14.44, 15.32]
	Qualcomm	[5.42, 6.57]	[10.19, 12.09]	[4.28, 4.90]	[10.10, 23.03]	[4.41, 4.76]	[4.41, 4.84]	[4.42, 6.80]	[-5.65, -5.03]
γ_2	Samsung	[4.56, 5.63]	[5.28, 6.84]	[4.67, 5.42]	[4.94, 7.71]	[4.52, 5.42]	[5.27, 5.69]	[4.71, 7.60]	[2.95, 3.52]
σ	Handset	[4.70, 5.33]	[5.08, 5.76]	[5.09, 5.88]	[4.80, 5.44]	[5.74, 6.30]	[7.13, 7.54]	[6.36, 7.21]	[10.80, 10.80]
	Qualcomm	[0.56, 1.92]	[2.25, 3.71]	[0.59, 0.73]	[3.03, 8.78]	[0.80, 0.98]	[0.78, 1.71]	[1.71, 2.19]	[2.07, 2.66]

I report the min and max of each parameter in the confidence set. The confidence set consists of a set of vectors of parameters that satisfy (9) and is not a Cartesian product of the intervals above.

4. The assumption of the finite horizon. I extend the game to end 12 months after the end of the sample. The time fixed effects in the demand function from $T+1$ to $T+12$ are extrapolated from the demand estimates in earlier periods.

5. The assumption of the sequential move. I assume that the firms move in the alternative order of Qualcomm, HTC, Samsung and Apple.

6. The initial state value of Qualcomm. I assume that the initial Qualcomm quality is 0.75 quality unit below its bound.

7. The initial state value of Qualcomm. I assume that the initial Qualcomm quality is 0.50 quality unit below its bound.

Table 12 reports the estimates in the robustness checks above, in addition to the estimates when the discount factor is set to 0.5. The estimates of the first seven checks are similar to Table 6. Tables 13 through (19) report the counterfactual results. All but one are consistent with the summary in Section 6. In the third exercise, the range of Samsung and Qualcomm innovate rates based on the sampled points are not all greater than 0, and neither is the (unreported) consumer and overall welfare measure. The increase in HTC innovation is still robust.

When the discount rate is lowered in the last column of Table 12, I obtain the implausible result that increasing Qualcomm quality actually decreases innovation costs. The exercises suggests that dynamic incentives are important in rationalizing the data.

I also consider the possibility that additional chipset producers may enter and compete with Qualcomm, if Qualcomm is integrated with HTC. I model this possibility as a decrease in $\bar{\psi}$. Table 20 reports the results when $\bar{\psi}$ is decreased by 10%. The pattern of increased innovation in the event of VI is robust.

Table 13: Counterfactual Result, Robustness Check 1

		No VI	Investment Coordination	Full VI
Innovation Rate: $(q_{36} - q_1)/35$	Apple	[0.0417, 0.0422]	[0.0430, 0.0433]	[0.0429, 0.0432]
	Samsung	[0.1023, 0.1198]	[0.1130, 0.1206]	[0.1146, 0.1221]
	HTC	[0.0831, 0.0884]	[0.0936, 0.0951]	[0.0950, 0.0960]
	Qualcomm	[0.0666, 0.0863]	[0.0785, 0.0868]	[0.0803, 0.0885]
			Difference %	
	Apple		[2.54%, 3.40%]	[-0.47%, -0.20%]
	Samsung		[-0.65%, 12.41%]	[0.86%, 1.49%]
	HTC		[7.36%, 13.26%]	[0.83%, 1.45%]
	Qualcomm		[-1.64%, 22.39%]	[1.35%, 2.28%]

Table 14: Counterfactual Result, Robustness Check 2

		No VI	Investment Coordination	Full VI
Innovation Rate: $(q_{36} - q_1)/35$	Apple	[0.0406, 0.0427]	[0.0417, 0.0436]	[0.0416, 0.0436]
	Samsung	[0.1037, 0.1125]	[0.1454, 0.1479]	[0.1458, 0.1488]
	HTC	[0.0833, 0.0888]	[0.0974, 0.0986]	[0.0976, 0.0986]
	Qualcomm	[0.0681, 0.0779]	[0.1138, 0.1177]	[0.1143, 0.1186]
			Difference %	
	Apple		[2.17%, 2.78%]	[-0.28%, 0.00%]
	Samsung		[31.16%, 40.23%]	[0.28%, 0.61%]
	HTC		[10.98%, 16.95%]	[0.03%, 0.18%]
	Qualcomm		[51.06%, 67.08%]	[0.43%, 0.79%]

Table 15: Counterfactual Result, Robustness Check 3

		No VI	Investment Coordination	Full VI
Innovation Rate: $(q_{36} - q_1)/35$	Apple	[0.0371, 0.0464]	[0.0386, 0.0472]	[0.0385, 0.0472]
	Samsung	[0.1042, 0.1153]	[0.1067, 0.1082]	[0.1070, 0.1085]
	HTC	[0.0834, 0.0889]	[0.0937, 0.0947]	[0.0939, 0.0951]
	Qualcomm	[0.0692, 0.0838]	[0.0732, 0.0743]	[0.0737, 0.0749]
			Difference %	
	Apple		[1.32%, 4.06%]	[-0.26%, -0.06%]
	Samsung		[-7.53%, 3.30%]	[0.24%, 0.43%]
	HTC		[6.09%, 12.69%]	[0.12%, 0.43%]
	Qualcomm		[-11.67%, 6.73%]	[0.59%, 0.91%]

Table 16: Counterfactual Result, Robustness Check 4

		No VI	Investment Coordination	Full VI
Innovation Rate: $(q_{36} - q_1)/35$	Apple	[0.0394, 0.0495]	[0.0400, 0.0502]	[0.0399, 0.0501]
	Samsung	[0.0928, 0.1091]	[0.1290, 0.1587]	[0.1297, 0.1594]
	HTC	[0.0647, 0.0940]	[0.0858, 0.1193]	[0.0865, 0.1195]
	Qualcomm	[0.0569, 0.0737]	[0.0989, 0.1271]	[0.0994, 0.1277]
			Difference %	
	Apple		[0.74%, 1.97%]	[-0.23%, 0.00%]
	Samsung		[18.16%, 49.86%]	[0.41%, 0.78%]
	HTC		[18.86%, 32.56%]	[0.22%, 0.81%]
	Qualcomm		[34.18%, 82.60%]	[0.45%, 1.14%]

Table 17: Counterfactual Result, Robustness Check 5

		No VI	Investment Coordination	Full VI
Innovation Rate: $(q_{36} - q_1)/35$	Apple	[0.0405, 0.0407]	[0.0410, 0.0412]	[0.0410, 0.0411]
	Samsung	[0.1030, 0.1070]	[0.1149, 0.1178]	[0.1155, 0.1180]
	HTC	[0.0745, 0.0854]	[0.0905, 0.0967]	[0.0909, 0.0969]
	Qualcomm	[0.0677, 0.0736]	[0.0824, 0.0851]	[0.0831, 0.0859]
			Difference %	
	Apple		[1.14%, 1.28%]	[-0.21%, 0.00%]
	Samsung		[9.57%, 14.29%]	[0.22%, 0.54%]
	HTC		[13.28%, 21.40%]	[0.15%, 0.51%]
	Qualcomm		[15.65%, 24.21%]	[0.55%, 0.88%]

Table 18: Counterfactual Result, Robustness Check 6

		No VI	Investment Coordination	Full VI
	Apple	[0.0380, 0.0443]	[0.0386, 0.0442]	[0.0385, 0.0442]
	Samsung	[0.0877, 0.1054]	[0.1352, 0.1436]	[0.1359, 0.1441]
	HTC	[0.0771, 0.0971]	[0.1067, 0.1307]	[0.1068, 0.1309]
Innovation Rate:	Qualcomm	[0.0752, 0.0910]	[0.1299, 0.1358]	[0.1308, 0.1367]
$(q_{36} - q_1)/35$			Difference %	
	Apple		[-0.34%, 1.68%]	[-0.45%, 0.00%]
	Samsung		[36.28%, 55.74%]	[0.30%, 0.53%]
	HTC		[34.61%, 41.07%]	[0.14%, 0.62%]
	Qualcomm		[46.73%, 74.50%]	[0.37%, 0.70%]

Table 19: Counterfactual Result, Robustness Check 7

		No VI	Investment Coordination	Full VI
	Apple	[0.0401, 0.0477]	[0.0404, 0.0476]	[0.0404, 0.0475]
	Samsung	[0.0895, 0.1054]	[0.1188, 0.1474]	[0.1198, 0.1481]
	HTC	[0.0566, 0.0778]	[0.0667, 0.1062]	[0.0667, 0.1066]
Innovation Rate:	Qualcomm	[0.0906, 0.1067]	[0.1200, 0.1510]	[0.1209, 0.1518]
$(q_{36} - q_1)/35$			Difference %	
	Apple		[-0.36%, 0.85%]	[-0.07%, 0.00%]
	Samsung		[27.74%, 58.66%]	[0.43%, 0.83%]
	HTC		[17.73%, 42.44%]	[0.04%, 0.30%]
	Qualcomm		[26.20%, 61.58%]	[0.51%, 0.78%]

Table 20: Vertical Integration with Potential Entry. Innovation Rate: $(q_{36} - q_1)/35$

	No VI $\bar{\psi}$	VI $0.9\bar{\psi}$
Apple	[0.0359, 0.0372]	[0.0414, 0.0454]
Samsung	[0.0979, 0.1064]	[0.1314, 0.1288]
HTC	[0.0666, 0.0674]	[0.0939, 0.0953]
Qualcomm	[0.0638, 0.0737]	[0.0979, 0.0993]