Vertical Structure and Innovation: A Study of the SoC and Smartphone Industries

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Abstract

This article studies how vertical integration and upstream R&D subsidy affect innovation and welfare in vertically separated industries. I formulate a dynamic structural model of a dominant upstream firm and oligopolistic downstream firms that invest in complementary innovations. I estimate the model using data on the System-on-Chip (SoC) and smartphone industries. The results suggest that a vertical merger can increase innovation and welfare, mainly driven by the investment coordination of the merged firms. I also find that subsidizing the upstream innovation increases overall private investment, innovation and welfare.

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), CPUs (upstream) and personal computers (downstream) and System-on-Chips (SoCs, upstream)

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and smartphones (downstream). The upstream innovations in these industries bear many similarities to the concept of "General Purpose Technologies" (GPT, Bresnahan and Trajtenberg (1995)): different downstream firms are consumers of the same upstream technology (pervasiveness), the upstream firms improve the technology over time (continuous improvement), and upstream innovations enable downstream innovations (innovation complementarity). Bresnahan and Trajtenberg (1995) points out an important under-innovation problem in a decentralized economy: firms fail to internalize the innovation complementarity because of the arms-length transactions between the GPT innovator and its users, and they under-innovate relative to the level of joint profit maximization. This article presents an empirical model of innovation in vertically separated industries and uses counterfactual simulations to quantify how vertical integration and upstream R&D subsidy may affect innovation and welfare.

The empirical context of this article is the innovation in the System-on-Chip (SoC) and smartphone industries. Since the introduction of the original iPhone, the smartphone industry has grown explosively. The global smartphone sales were 120 billion dollars in the last quarter of 2017 (Koetsier (2018)). The SoC is a key smartphone component that combines a mobile application processor (essentially a CPU), GPU, modem and other chips (Yang et al. (2014)). The SoC and smartphone industries provide an interesting setting to study innovation in vertically separated industries for a number of reasons. First, the SoC and smartphone innovations are strongly complementary. The enhanced processing power, energy efficiency and other functionalities from SoC innovations not only directly improve smartphone qualities, but also enable handset makers to adopt new designs. Secondly, vertical integration is a historically controversial subject in the mobile phone industry. Qualcomm, the dominant upstream firm in the SoC industry, was vertically integrated until 1999, and foreclosure was a main concern for many of Qualcomm's handset maker customers when Qualcomm was vertically integrated (Dingee and Nenni (2015)). Finally, the recent US-China trade disputes have renewed attention to government subsidy programs for R&D in the semiconductor sector (Jamrisko and Torres (2018)). Even before the recent events, the US government had been formulating plans to help upstream innovators, such as Intel and Qualcomm, with the belief that upstream innovations stimulate innovations across the economy (Holdren and Otellini (2016)). I use counterfactual simulations to explore the policy implication of an upstream subsidy to Qualcomm for the innovation in the SoC and smartphone industries.

To model the innovation and pricing of the SoCs and handsets, I consider a dynamic game of investment that nests a bargaining and pricing stage. The upstream industry consists of a dominant firm ("Qualcomm") and a non-strategic fringe, and the downstream firms are a finite number of oligopolistically competitive handset makers. In every period, Qualcomm and its downstream clients first negotiate SoC prices via Nash bargaining, and the handset makers then set wholesale prices in the Nash-Bertrand equilibrium. The subgame perfect equilibrium of the overall static Nash-in-Nash (Collard-Wexler, Gowrisankaran and Lee (2014)) pricing game determines the period profits. Modeling the bilateral negotiation between Qualcomm and handset makers allows me to quantify how a change in the market structure affects pricing in the counterfactual. I embed the implied profit functions in the dynamic game of upstream and downstream innovations. In the dynamic game, the upstream and downstream innovations are complementary: Qualcomm invests to increase the quality of its SoCs; downstream handset makers invest to increase the quality of their handsets, but the technological frontiers of some handset makers depend on that of Qualcomm. When deciding whether to innovate, upstream and downstream firms weigh the gains in the present discounted values of future profits due to the innovation against the sunk cost, and the dynamic innovation decisions form a Perfect Bayesian Equilibrium (PBE).

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 random coefficient logit model of consumer demand for smartphones. I refer to a linear combination of a product's characteristics, where the weights are given by the estimated demand coefficients, as the quality index of the product, and I use these indices to construct the quality frontiers of Qualcomm and handset makers. Next, I recover SoC prices and other marginal costs of smartphones using equilibrium pricing conditions and data on the markup of SoCs. The first two steps do not involve estimating the dynamic model. The estimates and the pricing equilibrium assumptions 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 functions. To keep the computation tractable, I estimate a dynamic game among the upstream Qualcomm and three handset makers: Apple, HTC and Samsung. Consistent with data, I assume that Apple uses its own SoCs, HTC exclusively uses the SoCs from Qualcomm, and Samsung sources both Qualcomm and non-Qualcomm SoCs. The quality of Qualcomm forms the upper bound on the technological frontiers of Samsung and HTC. I use a Simulated Minimum Distance estimator (Shi and Shum (2015)) to estimate the model.

Using the estimated model, I simulate two approaches to addressing the potential under-innovation problem. The first counterfactual considers a vertical merger between Qualcomm and HTC. This merger did not occur, but the simulation allows me to explore the magnitudes of various economic forces in vertical integration. The merged Qualcomm and HTC fully internalize their complementary innovations and jointly make innovation decisions.[1] The vertical integration also changes the pricing incentives. By endogenizing both the pricing and innovation decisions, I allow for and contrast the benefit of investment coordination between the merged firms and the potential harm from "raising rival's costs": the integrated upstream Qualcomm has an incentive to raise the SoC prices to a competing handset maker that buys SoCs from Qualcomm.[2] 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% (95% confidence set), and the innovation rate of the integrated HTC increases by 14% to 20%. Moreover, Samsung's innovation rate increases by 9% to 22%. Apple's innovation rate increases by less than 3%. Consumer surplus increases by 4% to 8%. I also find that investment coordination accounts for most of the gains from vertical integration. In terms of policy implications, the findings suggest that antitrust regulators should fully take into account the potential positive effect of coordinated investment in vertical integration, especially for innovative industries. My focus in this exercise is to quantitatively assess how vertical integration changes innovation by aligning incentives. Potentially vertical integration could allow the merged firms to specialize and realize additional gains by reducing marginal costs or lowering innovation costs.

The second counterfactual examines the effect of an upstream R&D subsidy. The existing empirical evidence is rather mixed on whether public subsidies crowd out private investment (David, Hall and Toole (2000); González, Jaumandreu and Pazó (2005)). Furthermore, whether a subsidy is welfare-enhancing (welfare increase greater than the amount of the subsidy) partly depends on the changes in consumer welfare. I examine whether the effect of a subsidy is more definitive when the upstream subsidized firm is similar to a GPT provider, whose faster innovation can stimulate

[1] 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)).

[2] An additional benefit of vertical integration is the elimination of double marginalization.

the innovations of multiple downstream firms. The results suggest upstream subsidies increase private investment and welfare. However, the effects on downstream firms are heterogeneous. A 10% subsidy of Qualcomm's R&D expenditures increases Qualcomm's innovation by 15% and Samsung's innovation by 11%, but has a much smaller positive effect (1.3%) on HTC. Apple's innovation slightly declines (-2%). Overall, the welfare effect of an upstream subsidy is large and positive, and the increase in the total surplus exceeds the amount of the subsidy.

Related Literature and Contribution The key modeling novelty in this article is the specification of dynamic upstream and downstream firms in vertical industries.[3] The model of innovation builds on the alternating-move, finite-horizon dynamic game in Igami (2017) by including an upstream innovator and considering complementary upstream and downstream innovations. The model of pricing nested in the dynamic game is related to the empirical bilateral bargaining framework (Crawford and Yurukoglu (2012)).[4] This type of models has been widely used to analyze the pricing of services and physical goods in vertical industries (within a static game).[5][6]

In addition, the modeling framework provides a natural measurement of upstream quality. For complex upstream products, it is generally hard to find direct measures of innovation except for a few cases (for example, the changes in benchmark scores for the desktop CPU in Goettler and Gordon (2011)). In the case of smartphone SoCs, benchmark scores reflecting the speed of the processors are available, but they do not capture the innovations in energy efficiency and graphic processing, which are both critical to the smartphone user experience. Because upstream innovations enable downstream firms to improve the measurable characteristics of downstream products, I instead use the "average appeal" of downstream products to the consumers to measure the quality of the upstream products in these downstream products: I construct a linear index based on the characteristics of the phones, where the coefficients are given by demand estimates. This linear index is part of the consumer utility function in the random coefficient logit demand

[3] This article is related to the vast literature on vertical structures. Lafontaine and Slade (2007) surveys the theoretical and (reduced-form) empirical literature.

[4] This empirical framework is based on Horn and Wolinsky (1988).

[5] Examples include Draganska, Klapper and Villas-Boas (2010), , Grennan (2013), Gowrisankaran, Nevo and Town (2014), Crawford et al. (2015) and Ho and Lee (2016).

[6] Like many papers in this literature (Brenkers and Verboven (2006); Murry (2015); Asker (2015); Crawford, Lee, Whinston and Yurukoglu (2015), in addition to those cited above), I assume that firms in my model use linear price contracts. I later discuss the pros and cons of this modeling choice in more details. Another strand of the empirical structural literature on vertical relations studies the pricing and welfare effects of alternative upstream-downstream relationships (e.g., Villas-Boas (2007); Mortimer (2008); Bonnet and Dubois (2010)).

model.

Road Map The rest of the article is organized as follows. 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 results of the counterfactual experiments. Section 7 considers three main robustness checks, and eight additional robustness analyses are available in Appendix D. I offer additional discussions of the model in Section 8 before concluding in Section 9.

2 Industry Background and Data[7]

SoC and Smartphone Innovation

A System-on-Chip (SoC) is a circuit that integrates a number of components critical to the operation of a smartphone. The processor (CPU) on an SoC handles the general computing needs, the GPU generates graphics, and many (but not all) SoCs also include other components, such as chips for broadband communications (modems), Wi-Fi, Bluetooth and GPS. During the sample period, Qualcomm was the leading provider of the SoCs in non-Apple phones, especially among the high-end phones. Apple designed its A-series SoCs on iPhones in-house. Apple did not sell its SoCs to other handset makers. In 2009, 53% of non-Apple smartphones sold in the US carried Qualcomm SoCs. Among high-end phones in 2009 (defined as those with retail prices above the median price in that year), 88% used Qualcomm SoCs. The US market share of Qualcomm among non-Apple phones increased to 72% in the first quarter of 2013, and the share among the high-end phones was around 73%. A number of firms, such as Texas Instruments (US), Freescale (US), NVIDIA (US) and Marvell (US), designed SoCs for smartphones but exited this market between 2009 and 2012. Samsung both designed its SoCs and made handsets, but also extensively used Qualcomm SoCs on its phones. During 2009-2013, Samsung's chip division and handset division operated independently, and I consider Samsung's handset division a vertically separated downstream firm.[8]

[7]This section is based on Mock (2005), Woyke (2014), Dingee and Nenni (2015), Findings of Facts and Conclusions of Law, FTC v. Qualcomm, Case No. 17-CV-00220-LHK, the author's data (2009-2013, US smartphone market) and cited sources therein.

[8]For example, Thomas Arenz, the head of marketing for Samsung Semiconductor then, said in a news report (Sakr (2014)) that "Samsung's component business can't engage in any sort of special relationship with Samsung Mobile for fear of losing the trust of other companies that buy Exynos chips (Samsung SoC) or other parts. ... There's no

The price of an SoC was typically between $16 and $40 (Woyke (2014)). Table 1 reports the origins of SoCs used in major non-Apple handset makers. According to reports published by iHS, a tear-down company that tracked smartphone component prices, the SoC accounted for 10% to 20% of the material cost of a smartphone.[9]

Developing an SoC is costly, and the main challenge is the design of the application processor. Apple and Qualcomm acquired independent chip designers and spent heavily on R&D. Apple, for example, spent about 400 million dollars on acquisitions alone and additional tens of millions on processor R&D (Gwennap (2012)). Several sources credited Qualcomm's ability to design better processors[10] and release new SoCs faster than its competitors as the main reasons for its dominant position in the SoC industry.[11]

In this article, I focus on the quality improvements of SoCs associated with each of Qualcomm's releases of new generations of SoCs. A majority of SoCs in the generation Snapdragon S1 were released in October 2008. Qualcomm's SoC 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. SoCs in a new generation feature significant gains in performance (more cores and higher frequency) and energy efficiency. Some aspects of the quality improvements in an SoC can be directly measured, such as the speed of the processor. However, unlike the CPU in a PC, some of the SoC's quality improvements are primarily reflected by changes in the design of a phone. For example, the improvement of the energy efficiency allows handset makers to use larger screens (Chen et al. (2013); Phone Arena (2015)) and smaller batteries (thus reducing the weight).

Following the release of a generation of Qualcomm SoCs, most major downstream handset makers (HTC, Samsung, LG and Motorola) adopted the new Qualcomm SoCs in (at least some of) their highest quality new handsets. I divide all SoCs into five generations, with the SoCs released

mechanism to ensure an Exynos chip ends up in a Galaxy phone."

[9]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.

[10]Qualcomm claimed that (for example, in Cheng (2012)) it was able to combine more functionalities on its SoCs than its competition, and this design could enhance performance and extend battery life.

[11]Major SoC makers license blueprints and tools from a British firm ARM to design the processors in the SoC. Although SoC makers use the same tools from ARM, how the processors are designed with these tools varies significantly. According to Dingee and Nenni (2015), "ARM offers canvas and paint through which designers large and small can express their vision of how things with a chip inside should work – the very essence of what makers do." Qualcomm is known to create highly customized processors based on the ARM blueprints. Dingee and Nenni (2015) notes that, "Qualcomm pushed Scorpion beyond the competition such as the TI OMAP 3 using a tuned Cortex-A8, and beat Intrinsity's "Hummingbird" core design to market by a bit more than two years."

before Qualcomm S1 labeled as the 0th generation, and the rest into four generations consistent with Qualcomm SoC generations. I classify non-Qualcomm SoCs into these generations based on the number of cores of the CPU, the clock speed and a variety of benchmark scores, broadband speed and GPU performances. Taking January 2009 as month 1, I document the time when Qualcomm announced the availability of a generation's SoCs and when a handset maker released a phone using that generation's SoCs (not necessarily Qualcomm's) in Table 2. Apple relied on its own proprietary SoCs, and a new generation of SoCs was used in a new generation of iPhones. The sampling of Qualcomm SoCs (when smartphone makers could officially test new Qualcomm SoCs on their prototype phones) started more than 5 months before the release of the phones.

Qualcomm's Licensing and Modem Businesses: 1990-2013

In this section, I first provide a brief historical account of the unique aspects of the mobile communication industry. I next discuss how these unique features affect the analysis of innovation in this empirical context.

Before the age of the smartphones and smartphone SoCs, Qualcomm was primarily known as an integrated firm in the mobile communication industry. Qualcomm pioneered a particular mobile communication technology, CDMA, in the late 1980's and early 1990's. Throughout the 90's, Qualcomm sold mobile phone CDMA communication chips (modems), CDMA base stations for wireless carriers and its own CDMA mobile phones (feature phones), in addition to licensing patents essential to the standards of wireless communication technologies. In the late 1990's, Qualcomm grew to be an important vertically integrated firm, and many of Qualcomm's handset customers were concerned that Qualcomm might have foreclosed them from the latest Qualcomm modems.[12] Downstream competitors threatened to develop modems based on alternative communication technologies. Had this plan materialized, Qualcomm not only would lose the modem businesses with these handset makers, but more importantly, might also lose patent revenues that depended on Qualcomm's technologies implemented in these modems. Qualcomm eventually sold its downstream handset division to Kyocera (a Japanese handset maker).

After the sale, Qualcomm conducted businesses primarily through Qualcomm CDMA Tech-

[12] "If Qualcomm built competing handsets or base stations, how could a third party compete? Many companies even suggested that Qualcomm, in order to keep a competitive advantage, reserved its latest and most cost-effective ASIC designs for its own products, leaving the leftovers for other parties." Mock (2005)

nologies (QCT), which operated Qualcomm's product and service businesses, and Qualcomm Technology Licensing (QTL), which oversaw the licensing of Qualcomm's patents. After smartphones became popular in the 2000's, Qualcomm started developing the application processors and SoCs for smartphones. The SoCs and standalone modems (called "thin modems") became Qualcomm's main products sold through QCT. At the same time, Qualcomm played a central role in setting the standards of the 2G, 3G and 4G cellular communication technologies and held essential patents for any smartphone to connect to a cellular network. As a result, through QTL, Qualcomm collected patent royalties on the wholesale price of effectively every smartphone even when a smartphone, such as an iPhone, used few Qualcomm chips. As the wholesale prices of high-end smartphones soared to more than 500 dollars in the 2000's, the licensing business became extremely profitable and the patent revenues accounted for more than 65% of Qualcomm's profits.[13] Qualcomm did not consider re-entering the handset market, and remained an upstream provider of components and intellectual properties.

To see how these institutional features affect my analysis on the innovations of the SoCs and downstream handsets, one needs to understand Qualcomm's conduct in three markets: SoCs, patent licensing and thin modems. As discussed in Section 2, Qualcomm faced competition in the SoC market. However, Qualcomm was a monopoly in both the licensing and the modem markets: a handset maker would not be able to build a phone if it did not have a license from Qualcomm or a modem, of which Qualcomm during the sample period was the only supplier.[14] At the same time, the licensing rates were subject to the "FRAND" rule (fair, reasonable and non-discriminatory), which in turns means that Qualcomm should offer similar licensing terms to all handset makers. Qualcomm interpreted the rule as applying a charge of about 5% to the wholesale prices of smartphones, similar to the rates Qualcomm used in the 1990's.[15] In the FTC v. Qualcomm case, the complaint against Qualcomm alleged that Qualcomm adopted a "no license-no chip" policy to enforce its patent licensing rates, threatening to cut off the supply of modem chips to any handset maker that disputed the licensing rate, as documented. As a result, handset

[13] Qualcomm financial statements, 2009-2013.

[14] Apple, for example, considered other thin modem suppliers such as VIA but found they did not meet its quality standard and lacked sufficient capacity.

[15] What should be considered a "reasonable" rate became a flash point of disputes between Qualcomm and handset makers, as reflected in the FTC v. Qualcomm case. The handset makers argued that due to the large investment made by handset makers on other aspects of a phone (touch screen, operating system, among others), Qualcomm's rate should be much lower.

makers effectively had two choices: they could choose to (1) buy thin modems from Qualcomm and obtain SoCs from a difference source; or (2) buy the SoCs integrated with modems from Qualcomm. Apple chose (1) by building its own SoCs and using Qualcomm's thin modems. HTC and many other Android phone makers chose (2), whereas Samsung sourced both the thin modems and SoCs from Qualcomm. Regardless of their choices, handset makers during my sample period paid patent royalties to Qualcomm.

To showcase the economic tradeoffs in the innovation decisions of SoCs and handsets, I do not model the sale of thin modems and patent licensing in the baseline model. I then expand the analysis by modeling Qualcomm's profits as the SoC profits plus a weighted sum of the revenues of downstream handset makers. This exercise captures the key idea that Qualcomm was an innovator that internalized the benefit of the downstream innovations more than a stylized upstream GPT provider in Bresnahan and Trajtenberg (1995).

A different issue is whether Qualcomm would be better off as a vertically integrated supplier of SoCs, had Qualcomm continued to own a handset division, and other downstream firms switched to a different cellular standard, which would imply that Qualcomm would lose the patent revenues and possibly the thin modem business. I show that it is unlikely Qualcomm would be better off if it loses the patent revenues when merged with a downstream firm: in another counterfactual simulation, the surplus of the integrated HTC and Qualcomm that does not receive the patent royalties is lower than the joint surplus of the independent HTC and Qualcomm that has patent royalties. I offer additional discussions on how Qualcomm's conduct in the licensing and modem markets affects my analysis in Section 8 after presenting the full model and results.

Data

The smartphone quantity and price data used in this article are from ITG Market Research, and the information on a phone's SoC and other characteristics is collected 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. During the sample period, Qualcomm was an independent upstream supplier of SoCs. Therefore my empirical approach is to estimate a model where Qualcomm is vertically separated from the downstream, and use counterfactual simulations to understand the effects if Qualcomm were merged with a downstream firm. The observation is at the handset-carrier-month level. In Table 3, I document the retail revenues and quantities of phones sold by the major handset makers. Although BlackBerry sold many low-end handsets in the first year of the data, its sales decreased sharply in later years. Apple, Samsung and HTC accounted for 70% of sales (quantity) in the sample, and the top five producers in Table 3 accounted for 95%.

The data show that during the sample period, new and better smartphones arrived on the market around the year. Several key dimensions of the smartphone quality, in addition to the generation of the SoC, 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.

The US market accounted for about 15% of the global shipment in Q4 2011 (Gartner (2012)), but was 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, and this proportion was relatively constant throughout the sample period. In this article, I assume that the US market accounts for a constant proportion of the world market.

Although I do not observe SoC prices directly, I collect the accounting gross margin data of Qualcomm from its quarterly financial reports. The gross margin is defined as

$$\frac{\text{chip sales} - \text{cost of chips}}{\text{chip sales}}, \tag{1}$$

where the cost includes manufacturing, handling, inventory and other costs. Investment, fixed costs (in the accounting sense) or the royalty revenues are not included. In the data, 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%. I use the data as the sales-weighted average gross margin of Qualcomm SoCs. The average gross margin data interpreted this way allow me to impute product-specific SoC prices, detailed in Section 5. There are two potential issues with using the accounting data. First, these gross margin data may not reflect the true economic markup. In addition, Qualcomm also sold Wi-Fi chips and standalone modems, and financial reports do not itemize the gross margins by the types of chips. I therefore conduct robustness checks by perturbing the gross margin data in Appendix D.

3 A Dynamic Model of Upstream and Downstream Innovation

Time is discrete $t = 1, 2, \ldots, T$. The upstream industry consists of Qualcomm and a non-strategic fringe. The downstream industry consists of a finite and fixed set of firms $\mathcal{N}$. I will first discuss the state variables, and their roles in the model will be clear later. Qualcomm's state variable is the quality frontier q^Q. The upstream fringe affects the period payoff, but does not directly affect the innovation decisions, and I discuss the role of the fringe in Section 4. There are three different downstream firms in $\mathcal{N}$:

1. Apple is fully integrated and its SoC innovation and handset innovation occur simultaneously. Because Apple designs its own SoCs, it can innovate above Qualcomm's frontier. In other words, it is possible that the quality of Apple $q^{Apple} > q^Q$.

2. Samsung chooses to use Qualcomm SoCs on some of its handsets. As discussed in Section 2, I focus on Samsung's handset division here. Samsung does not innovate above Qualcomm's quality level: $q^{Samsung} \leq q^Q$.[16] To avoid the complication of modeling how Samsung chooses the SoC for each handset, I assume that Samsung uses a number η to decide which phones use Qualcomm SoCs probabilistically. The fraction η is interpreted as the proportion of Samsung handsets using Qualcomm SoCs. I describe how η affects Samsung's payoff in Appendix B.

3. HTC uses Qualcomm SoCs for all HTC handsets. HTC does not innovate above Qualcomm's quality level: $q^{HTC} \leq q^Q$.

The industry state consists of $s = \left\{t, q^Q, q^{Apple}, q^{Samsung}, \eta^{Samsung}, q^{HTC}\right\}$. Each firm corresponds with the following set of actions: in every period,

1. Qualcomm chooses the quality increment of its frontier, $a^Q \in \{0, \mathit{\Delta}, 2\mathit{\Delta} \ldots, K_1\mathit{\Delta}\}$, and in the next period, the state of Qualcomm transitions to $q^Q_{t+1} = q^Q_t + a^Q$. The action in the data that corresponds with Qualcomm's innovation is its release of new SoCs.

[16] There are at least two reasons to think Qualcomm's quality frontier was a constraint for Samsung during my sample period. The production capacity for Samsung's own Exynos was limited, likely due to low yield (Sakr (2014)), and Samsung needed to use both Exynos and Qualcomm for the same high volume flagship products such as Galaxy S5. J K Shin, the Samsung's chief executive and head of mobile communications in 2013, suggested in a news report (Tibken (2013)) that Samsung sourced both chip variants to ensure it had enough supply. In addition, Qualcomm Snapdragon S4 supported 4G LTE, the new communication technology in major markets such as US and Europe, but the same generation's Samsung Exynos SoC did not.

2. Apple chooses the quality increment $a_q^{Apple} \in \{0, \delta, 2\delta, \ldots, K_2\delta\}$, and the next period Apple's state transitions to $q_{t+1}^{Apple} = q_t^{Apple} + a_q^{Apple}$. The release of every new generation of iPhones corresponds with a new SoC, and Apple SoCs are exclusively used on its own handsets. I therefore do not separately model Apple's SoC and handset innovation decisions and assume that with one innovation, Apple updates both the SoCs and handsets.

3. Samsung chooses the quality increment $a_q^{Samsung} \in \{0, \delta, 2\delta, \ldots, K_2\delta\}$, and if Samsung indeed innovates ($a_q^{Samsung} > 0$), Samsung also chooses the proportion $a_\eta^{Samsung} \in \{0.3, 0.5, 0.7\}$ of post-innovation handsets that use Qualcomm SoCs.[17] The transition of Samsung's states $\left(q^{Samsung}, \eta^{Samsung}\right)$ can be summarized as follows:

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

4. HTC chooses the quality increment $a_q^{HTC} \in \{0, \delta, 2\delta, \ldots, K_2\delta\}$, and the next period HTC's state transitions to $q_{t+1}^{HTC} = q_t^{HTC} + a_q^{HTC}$.

The game starts in $t = 1$ and ends in T. At the beginning of every period, firms receive period profits. Firms then make dynamic decisions sequentially. Qualcomm's period profit $\pi_t^Q(s_t)$ and handset maker n's period profit $\pi_t^n(s_t)$ are given by a pricing game to be detailed in Section 4. The profit functions capture the non-stationarity in demand and marginal costs, in addition to taking into account the strategic SoC pricing between Qualcomm and handset makers and the strategic handset pricing. Qualcomm moves first, and handset makers move in the sequence of Apple, Samsung and HTC:

- Qualcomm draws an i.i.d. private shock ε_t^Q to the innovation cost, chooses an action a_t^Q and pays a sunk cost of $C^Q\left(a_t^Q, \varepsilon_t^Q\right)$.
- Apple observes Qualcomm's innovation decision, draws an i.i.d. private shock ε_t^{Apple}, chooses an action a_{qt}^{Apple} and pays $C^{Apple}\left(a_{qt}^{Apple}, \varepsilon_t^{Apple}\right)$

[17]This assumption is consistent with data. In Fig. 2, I show that most changes of η are associated with innovations, and between two consecutive innovations, η is roughly constant.

- Samsung observes the innovation decisions of Qualcomm and Apple, draws an i.i.d. private shock $\varepsilon_t^{Samsung}$, chooses an action $\left(a_{qt}^{Samsung}, a_{\eta t}^{Samsung}\right)$ and pays $C^{Samsung}\left(a_{qt}^{Samsung}, a_{\eta t}^{Samsung}, \varepsilon_t^{Samsung}\right)$. Samsung's innovation is subject to the constraint $q_t^{Samsung} + a_{qt}^{Samsung} \leq q_{t+1}^{Q}$.

- HTC observes the innovation decisions of Qualcomm, Apple and Samsung, draws an i.i.d. private shock ε_t^{HTC}, chooses an action a_{qt}^{HTC} and pays $C^{HTC}\left(a_{qt}^{HTC}, \varepsilon_t^{HTC}\right)$. The innovation of HTC is subject to the constraint $q_t^{HTC} + a_{qt}^{HTC} \leq q_{t+1}^{Q}$.

- A new period starts.

In the last period, each firm receives a terminal value $\dfrac{\pi_T^{\cdot}(s_T)}{1-\beta}$.

I next characterize each firm's optimization problem. For each firm, the value function V is defined as the present discounted value at the beginning of a period, before the firm receives the period payoff. I start with Qualcomm. Qualcomm's information set consists of the current state s_t, and Qualcomm's own private shock ε_t^Q in the current period. For a given state s, Qualcomm also knows $\pi_t^Q(s)$ and $\pi_t^n(s)$ for every t. Furthermore, Qualcomm knows the functional form of the innovation cost functions $C^{Apple}, C^{Samsung}$ and C^{HTC}, and the distribution of the corresponding private cost shocks, but not their realizations. Qualcomm forms a belief about the actions of the firms that have not moved. Qualcomm in period t solves

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

where the expectation is taken over Qualcomm's belief about the actions of firms that have not moved in period t, and δ is the discount factor. Qualcomm's best response $a_t^{Q\star}$ is the solution to this optimization problem in t, and $a_t^{Q\star}$ is a function of Qualcomm's private cost shock and the current state. The value function of Qualcomm satisfies the Bellman equation

$$V_t^Q(s_t) = \pi^Q(s_t) + \int_{\varepsilon_t^Q}\left\{-C^Q\left(a_t^{Q\star}, \varepsilon_t^Q\right) + \delta E\left(V_{t+1}^Q(s_{t+1})\,\middle|\, s_t, a^{Q\star}\right)\right\}. \tag{2}$$

When it is handset maker n's turn to move, the handset maker's information set consists of the state s_t, the own private shock ε_t^n and the actions of firms that have moved, in addition to the functional form of all firms' innovation cost functions and the distributions of other firms' private cost shocks. For a given state s, the handset maker also knows $\pi_t^Q(s), \pi_t^n(s)$ for every t. Below, I use $a_t^{n\star}$ to denote the best response of firm n in period t, and $a_t^{n\star}$ is a function of the state s_t, the own private shock and the actions of firms that have moved. Handset makers form beliefs about Qualcomm and rival firms' actions. Apple solves

$$\max_{a_q^{Apple}} \left(-C^{Apple}\left(a_q^{Apple}, \varepsilon_t^{Apple}\right) + \delta E\left(V_{t+1}^{Apple}(s_{t+1}) \middle| s_t, a_t^Q, a_q^{Apple}\right)\right).$$

The expectation is taken over Apple's belief about the actions of Samsung and HTC. The optimization problem characterizes Apple's best response $a_{qt}^{Apple\star}$ in t as a function of the state, ε_t^{Apple} and Qualcomm's move. Because s_{t+1} is fully determined given the vector

$$\left(s_t, a_t^Q, a^{Apple}, a_q^{Samsung}, a_\eta^{Samsung}, a_q^{HTC}\right),$$

the value function can be written as

$$\begin{aligned} V_t^{Apple}(s_t) = \pi_t^{Apple}(s_t) + E_{\varepsilon_t^{Apple}, a^Q, a_q^{Samsung}, a_\eta^{Samsung}, a_q^{HTC}} \Big[& -C^{Apple}\left(a_{qt}^{Apple\star}, \varepsilon_t^{Apple}\right) \\ & + \delta V_{t+1}^{Apple}\left(s_{t+1}\left(s_t, a_t^Q, a_{qt}^{Apple\star}, a_q^{Samsung}, a_\eta^{Samsung}, a_q^{HTC}\right)\right)\Big], \end{aligned}$$

where the expectation is taken over ε_t^{Apple} and Apple's belief about the actions of non-Apple firms in t. The action probabilities are correlated across firms because of the sequential move assumption.

Samsung solves

$$\begin{aligned} \max_{a_q^{Samsung}, a_\eta^{Samsung}} & -C^{Samsung}\left(a_q^{Samsung}, a_\eta^{Samsung}, \varepsilon_t^{Samsung}\right) \\ & + \delta E\left(V_{t+1}^{Samsung}(s_{t+1}) \middle| s_t, a_t^Q, a_t^{Apple}, a_q^{Samsung}, a_\eta^{Samsung}\right) \\ s.t. q_t^{Samsung} & + a_q^{Samsung} \le q_{t+1}^Q \end{aligned}$$

The expectation is taken over Samsung's belief about the actions of HTC. The Bellman equation is

$$V_t^{Samsung}\left(s_t\right) = \pi_t^{Samsung}\left(s_t\right) + E_{\varepsilon_t^{Samsung}, a^Q, a_q^{Apple}, a_q^{HTC}}\left[-C^{Samsung}\left(a_{qt}^{Samsung\star}, a_{\eta t}^{Samsung\star}, \varepsilon_t^{Samsung}\right)\right.$$
$$\left. + \delta V_{t+1}^{Samsung}\left(s_{t+1}\left(s_t, a^Q, a_q^{Apple}, a_{qt}^{Samsung\star}, a_{\eta t}^{Samsung\star}, a_q^{HTC}\right)\right)\right].$$

The expectation is taken over $\varepsilon_t^{Samsung}$ and Samsung's belief about the actions of non-Samsung firms.

HTC solves

$$\max_{a_q^{HTC}} - C^{HTC}\left(a_q^{HTC}, \varepsilon_t^{HTC}\right)$$
$$+ \delta V_{t+1}^{HTC}\left(s_{t+1}\left(s_t, a_t^Q, a_t^{Apple}, a_{qt}^{Samsung}, a_{\eta t}^{Samsung}, a_q^{HTC}\right)\right)$$
$$s.t. q_t^{HTC} + a_q^{HTC} \leq q_{t+1}^Q$$

The Bellman equation is

$$V_t^{HTC}\left(s_t\right) = \pi_t^{HTC}\left(s_t\right) + E_{\varepsilon_t^{HTC}, a^Q, a_q^{Apple}, a_q^{Samsung}, a_\eta^{Samsung}}\left[-C^{HTC}\left(a_{qt}^{HTC\star}, \varepsilon_t^{HTC}\right)\right.$$
$$\left. + \delta V_{t+1}^{HTC}\left(s_{t+1}\left(s_t, a^Q, a_q^{Apple}, a_q^{Samsung}, a_\eta^{Samsung}, a_{qt}^{HTC\star}\right)\right)\right].$$

The expectation is taken over ε_t^{HTC} and HTC's belief about the actions of non-HTC firms. I solve for the Perfect Bayesian Equilibrium. In the PBE, the beliefs are rational and consistent with the true action probabilities.

Qualcomm's innovation cost is specified as a function of the size of the innovation step and its own private shock:

$$C^Q\left(a^Q, \varepsilon_t^Q\right) = \begin{cases} 0, & a^Q = 0 \\ \exp\left(\gamma_0^Q + \gamma_1^Q a^Q + \sigma^Q \varepsilon_t^Q\right) & a^Q > 0 \end{cases} \tag{3}$$

Apple's innovation cost is

$$C^{Apple}\left(a_q^{Apple},\varepsilon_t^{Apple}\right)=\begin{cases}0, & a_q^{Apple}=0\\ \exp\left(\gamma_0^{Apple}+\gamma_1^{Apple}a_q^{Apple}+\sigma^{Apple}\varepsilon_t^{Apple}\right) & a_q^{Apple}>0.\end{cases} \tag{4}$$

Unlike other handset makers, Apple is vertically integrated. Every time Apple introduces a new generation of phones, Apple also updates the SoCs. Therefore Apple's innovation cost should be interpreted as the sum of SoC and handset development costs.

The innovation cost of Samsung is

$$C^{Samsung}\left(a_q^{Samsung},a_\eta^{Samsung},\varepsilon_t^{Samsung}\right)=\begin{cases}0, & a_q^{Samsung}=0\\ \exp\left(\gamma_0^{Samsung}+\gamma_1^{Samsung}a_q^{Samsung}\right.\\ -\gamma_2^{Samsung}a_\eta^{Samsung}\\ \left.+\sigma^{Samsung}\varepsilon_t^{Samsung}\right) & a_q^{Samsung}>0.\end{cases} \tag{5}$$

The innovation cost of HTC is

$$C^{HTC}\left(a_q^{HTC},\varepsilon_t^{HTC}\right)=\begin{cases}0, & a_q^{HTC}=0\\ \exp\left(\gamma_0^{HTC}+\gamma_1^{HTC}a_q^{HTC}+\sigma^{HTC}\varepsilon_t^{HTC}\right) & a_q^{HTC}>0.\end{cases} \tag{6}$$

The cost shocks $\varepsilon_t^{\cdot}$ are i.i.d and standard normal. In the innovation cost functions above, I allow each handset maker to have different coefficients for both the intercept and the mean to capture the large heterogeneity between them. The coefficients of Apple account for the innovation costs of the SoC and handsets; the coefficients of Samsung account for the handset innovation costs and the cost reduction if more handsets use Qualcomm SoCs. I also assume that the cost exponentially increases in the step size of an innovation, so that the chance of an extremely large innovation is rare.

I assume that the innovation game has a finite horizon and firms move sequentially. These two assumptions provide three crucial benefits: (1) the dynamic equilibrium is unique (by backward induction), (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. These two assumptions have also been used in Igami (2017) for similar purposes. I assess the sensitivity of the results to the finite horizon assumption in Section 7 and the sequential move assumption in Appendix D.

In this model, I assume that the dynamic innovation decisions are not contractible. In other words, HTC cannot enter into a contract with Qualcomm about the future qualities of Qualcomm SoCs before Qualcomm's innovation is realized. Such contracts could effectively achieve vertical integration. Grossman and Hart (1986), Hart and Moore (1990) and others have shown that without investment coordination, two vertically separated monopolists would invest below the joint profit maximizing level because neither firm fully internalizes the benefit of investment for the other firm. Central to the concept of "incompleteness" in the model above is the difficulty of communicating a firm's innovation decisions to others before the realization of the innovation. Although the technological capability of a firm is abstracted into a scalar q in the model, coordinating innovations in the real world potentially would require the SoC maker and handset makers to agree on the joint development of many dimensions of the technology. Identifying and agreeing to the exact nature of an innovation may be hard enough in the face of an uncertain future demand and complex product designs.[18] 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. Furthermore, had the industry been coordinated by contracts that internalized the externalities of pricing and innovation, the distinction between a separated firm and an integrated firm would exist merely in name, and handset makers would not have been so concerned with an integrated Qualcomm in the 1990's. Given these considerations, I assume that firms cannot contract on future innovations.

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 SoC releases and "punish" HTC, if HTC does not pay Qualcomm a transfer or commit to Qualcomm SoCs after a Qualcomm innovation. The assumptions of a finite horizon and sequential moves in my model have the effect of a Markov refinement and

[18] Woyke (2014) described the handset design process at Sony. Designers sometimes work independently for over a year before meeting with engineers to discuss technological constraints, and many compromises were made subject to the constraints of existing technologies during the last few months before the designs were turned into prototypes.

eliminate the cooperative equilibria. In an infinite horizon game, the folk theorem suggests that upstream and downstream firms can play cooperatively if the discount factor δ 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 (e.g., Halonen (2002); Baker et al. (2002); Che and Sákovics (2004); Che and Sákovics (2007)).

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 such as ς requires excluded demand shifters (Bresnahan (1982); Berry and Haile (2014)) or data on innovation costs. In Section 5, I discuss how investment data can inform ς.

4 Bargaining Model

This section describes a static model of bargaining that determines the profit function $\pi_t(s_t)$ used as input to the dynamic model. I assume that prices are set in the following order:

1. Qualcomm and handset makers negotiate SoC prices via Nash bargaining.
2. Handset makers take the SoC prices and other components of the marginal costs as given and set wholesale prices.

I start with the demand function.

Consumer Demand

I model the consumer demand for smartphones using a random coefficient logit model (Berry, Levinsohn and Pakes (1995)). A product is defined as a phone-model-carrier pair (e.g. Galaxy S3 on T-Mobile or iPhone 4S on ATT),[19] and a consumer is indexed by i and a product is indexed by j (Galaxy S3 on T-Mobile and Galaxy S3 on ATT are thus indexed by two different j's). I use $n(j)$ and $c(j)$ to denote the manufacturer and carrier of j. The utility of consumer i purchasing j

[19] Fan and Yang (2019) documents that 88% of the phones are sold through a single carrier.

in period t is

$$\begin{aligned} u_{ijt} &= \beta_{0i} q_j - \alpha p_{jt} + \theta_{n(j)} + \kappa_{c(j)t} + \xi_{jt} + \epsilon_{icjt} \\ &= \underbrace{\bar{\beta}_0 q_j - \alpha p_{jt} + \theta_{n(j)} + \kappa_{c(j)t} + \xi_{jt}}_{\mu_{jt}} + \sigma \nu_i q_j + \epsilon_{ijt} \end{aligned} \tag{7}$$

where $q_j = x_j \beta$ is the linear quality index based on product characteristics x_j and a vector of parameters β, 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, $\theta_{n(j)}$ is the handset maker brand fixed effect, $\kappa_{c(j)t}$ is the carrier-year fixed effect plus a 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 article), 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, SoC 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). The mean consumer utility is denoted as μ_{jt}, and the utility of no purchase is normalized to zero plus an i.i.d type I extreme value shock $\epsilon_{i\emptyset t}$. The demand for j is given by

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

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. The market size used in the estimation is 30 million, about 10% of the U.S. population during the sample period. In Section 7, I use an alternative market size based on the total unit sales of smartphones and feature phones. I next discuss the pricing of smartphones and SoCs.

Smartphones Prices

I denote the set of handset maker n's products as $\mathcal{J}_{nt}$. Given the SoC 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-SoC marginal cost of a smartphone is specified as a function of observed characteristics plus a shock:

$$\omega_{jt} \equiv \underbrace{\lambda_q \exp\left(q_{jt}\right) + \lambda_{n(j)} + \lambda_{Q(j)} + \zeta_{c(j)t}}_{\substack{\text{quality, handset maker FE} \\ \text{use Qualcomm?} \\ \text{carrier-time FE}}} + \underbrace{\varkappa_{jt}}_{\text{shock}} . \tag{8}$$

The retail price is marked down from the wholesale price. In the US market between 2009 and 2013, most of the smartphones were sold through carriers via two-year contracts. The carriers marked down the wholesale price substantially and made profits back from service fees that the consumers had to pay every month for two years. Most notably, carriers sold each generation's latest iPhone models for about \$200 before 2013, but the wholesale prices were above \$600 (Fan and Yang (2019)). I assume that the carrier markdown on product j is specified as

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

and the retail price is $p_{jt} = w_{jt} - r_{jt}$. In effect, I assume that carrier markdowns r_{jt} are given by a simple linear rule based on the set of covariates in Eq. (8). The primary purpose of this assumption is to simplify the computation of handset maker and Qualcomm's profits by avoiding adding another stage in the pricing game. This assumption abstracts away from carriers' strategic pricing, but still allows carrier prices to depend on key handset characteristics such as the product qualities. Handset maker n's profit maximization problem can be re-written as

$$\max_{p_{jt}, j \in \mathcal{J}_{nt}} \sum_{j \in \mathcal{J}_{nt}} \left(p_{jt} - \psi_{jt} - \left(\omega_{jt} - r_{jt}\right)\right) D_{jt}, \tag{9}$$

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

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

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

$$p - \psi - \omega = (L * \Delta)^{-1} D, \tag{10}$$

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 the SoC on 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 fix the pricing equilibrium selection mechanism 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 (10) as a fixed point mapping to solve for the equilibrium prices. In practice, I find that this procedure always converges numerically to a unique price vector $p^\star$. The downstream firm n's variable profit is denoted as $\pi_t^n(\boldsymbol{\psi}_t)$ in (9) given SoC prices $\boldsymbol{\psi}_t$ and $D^\star = D(p^\star)$ to denote the derived demand for SoCs.

Nash Bargaining and SoC Prices

The bargaining game in the first stage of the static game determines the equilibrium SoC prices between Qualcomm and handset makers. I first write down Qualcomm's profit function. Qualcomm earns profits from SoC 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's SoC and $\underline{\psi}$ is the marginal cost for Qualcomm to produce an SoC.[20] Qualcomm negotiates with each handset maker n separately. Denote the vector of SoC prices specific to a Qualcomm-n bargaining pair as $\boldsymbol{\psi}_{nt} = (\psi_{jt}, j \in \mathcal{J}_{Qt} \cap \mathcal{J}_{nt})$. The SoC prices are set in a bargaining equilibrium:

Definition. *(Nash-bargaining equilibrium)* SoC 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,

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

conditional on other SoC prices $\boldsymbol{\psi}_{-nt}$:

$$\left[\pi_t^Q\left(\boldsymbol{\psi}_{nt}, \boldsymbol{\psi}_{-nt}\right) - \tilde{\pi}_t^Q\left(\boldsymbol{\psi}_{-nt}\right)\right]^{\tau_t} \cdot \left[\pi_t^n\left(\boldsymbol{\psi}_{nt}, \boldsymbol{\psi}_{-nt}\right) - \tilde{\pi}_t^n\left(\boldsymbol{\psi}_{-nt}\right)\right]^{1-\tau_t}, \tag{11}$$

where $\tilde{\pi}$ is the disagreement payoff, and τ_t is the bargaining weight in period t.[21]

For $\tilde{\pi}$, I assume that when the negotiation breaks down, the handset maker n uses alternative functionally identical SoCs at price $\bar{\psi}$ for handsets in $\mathcal{J}_{Qt} \cap \mathcal{J}_{nt}$ (so the handset qualities remain the same, but the cost of the SoC is $\bar{\psi}$), and Qualcomm loses SoC revenues from the handset maker. Other SoC prices are held fixed and the downstream pricing equilibrium is recalculated. I thus implicitly assume that the frontier of the fringe SoC is equal to Qualcomm's frontier. This assumption is a strong form of spillover effects: the fringe SoC quality increases to Qualcomm's level after Qualcomm innovates. Realistically, the handset quality may also change if a non-Qualcomm SoC is used. I consider this possibility in a robustness check in Appendix D, where I assume that the fringe SoC quality trails Qualcomm's quality by a fixed amount, and that the phone quality decreases if the handset maker switches to the non-Qualcomm SoC.

Based on Eq. (11) and the definition of Nash bargaining equilibrium, the vector of prices of all Qualcomm SoCs ψ satisfies the following first order condition:

$$\psi = \underline{\psi} + \Theta^{-1}\Phi, \tag{12}$$

where Θ and Φ are defined in Appendix A.In this model, Qualcomm does not strategically choose which SoCs to terminate (make them no longer available to the handset makers).

The assumption of linear contracts between handset makers and Qualcomm simplifies the contract space and keeps the computation tractable, but there are several downsides. First, this assumption introduces double marginalization, an inefficiency that vertical integration can reduce. Based on Qualcomm's gross margin data, I use linear contracts to approximate the variable profits of Qualcomm and handset makers. When the terms in (1) that define the gross margin are close to the true economic primitives and the inefficiency of linear contracts is small compared with the total value of the contracts, the approximated variable profits should also be close to the true variable

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

profits. I examine the robustness of the results to potential measurement errors in the gross margin data in Appendix D, and Section 6 demonstrates that the inefficiency of linear contracts (double marginalization) is indeed small. Another concern is whether the linear contract assumption limits firms from achieving innovation coordination. Importantly, it should be recognized that even an ex post efficient contract that divides the surplus between the upstream and downstream firms can still lead to under-investment (Grossman and Hart (1986)). As shown in Section 6, the assumption of "ex post negotiation" is the main reason why firms cannot coordinate innovation in this model.

I also assume that firms renegotiate prices monthly. In reality, prices might change less often.[22] The misspecification of the price-setting frequency introduces mean-zero measurement errors in profits if firms have rational expectations. For my focus on the dynamics of innovation, I assess the potential bias of my profit estimates. I first calculate the sales-weighted average SoC price on each handset for six-month periods of January-June 2009, July 2009-Dec 2009, ... based on the imputed SoC prices explained in Section 5. I next calculate the alternative Qualcomm and handset maker profits in month t if they instead use the average SoC prices corresponding with the six-month period that contains t. I find the average difference of the monthly profit (for either Qualcomm or handset makers) to be less than 3%.

Period Profit

I first define a vector y that collects the number of products, product qualities, SoC origins and carrier-time fixed effects. Using the equilibrium selection rules above, Qualcomm and handset maker profits can be written as a function of y, demand shocks and marginal cost shocks, $\pi_t^Q(y, \xi, \varkappa, \tau)$ and $\pi_t^n(y, \xi, \varkappa, \tau)$. Note that y does not include the state variable of Qualcomm.

In this article, I focus on how firms adjust quality frontiers, and assume that y is a realization from the distribution $g(Y; \tilde{s}_t, \theta)$: the set of products is a random variable that has a stationary distribution conditional on the state variables defined in Section 3,[23] where $\tilde{s}_t$ is a vector of handset 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 is detailed in Appendix B. I further assume that Y, ξ, $\varkappa$ and τ_t are distributed independently. Firms use $\pi_t^Q(s_t) \equiv$

[22]Some technology news outlets suggest that Qualcomm changes prices quarterly (e.g. technews.co (2014)).
[23]See Fan and Yang (2019) for a study on product variety.

$\pi_t^Q(\tilde{s}_t) \equiv E_{Y,\xi,\varkappa,\tau|\tilde{s}_t}\left(\pi_t^Q(Y,\xi,\varkappa,\tau)\right)$ and $\pi_t^n(s_t) \equiv \pi_t^n(\tilde{s}_t) \equiv E_{Y,\xi,\varkappa.\tau|\tilde{s}_t}(\pi_t^n(Y,\xi,\varkappa,\tau))$ to make dynamic innovation decisions. The assumptions that (1) all firms use the expected profits when making innovation decisions and (2) demand shocks are independent of Y justify the use of BLP-type (Berry et al. (1995)) instruments for demand estimation in the next section.

Using a static model also has another important practical advantage. 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 needs to be done just 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 inputs to the estimation and simulation of the dynamic game. In reality, smartphones are both durable goods and network goods (e.g., Sinkinson (2014); Luo (2016)). Although the framework in this article does not include dynamic consumers or 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 dynamic pricing of SoCs. Qualcomm may offer handset makers a discount to be used in more phones for several periods. The innovation cost parameter γ_2^n in (4) partially captures this possibility. When γ_2^n is positive, the innovation cost decreases if n uses Qualcomm SoCs on more of its handsets. γ_2^n may reflect 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. I do not find counterfactual simulation results sensitive to perturbations to the estimates.

The institutional context of the smartphone market in the US (and similarly a number of other advanced economies such as Japan, South Korea, France and Canada) provides some justification for considering a static model. During the sample period, most US consumers purchased subsidized smartphones through a contract with the wireless carriers, and such a contract required a consumer to use the same phone and carrier for two years. Surveys (for example Entner (2011)) show that most people in the US purchased new phones every two years between 2007 and 2010, coinciding with the typical length of a contract. The model assumes that the arrival of the new consumers is exogenous as a result of contract expiration and the immediate need to replace the old phones.[24]

5 Identification and Estimation

In this section, I discuss the identification and estimation of the bargaining model and the dynamic innovation model. In the bargaining model, there are three sets of structural parameters to be estimated: the consumer preference parameters for smartphones $(\beta, \alpha, \theta, \kappa, \sigma)$ in (7), the smartphone marginal cost parameters λ in (8) and the bargaining weights τ in (11) (I omit the time subscript t here for brevity). I calibrate the price of the replacement SoC $\bar{\psi}$ and the marginal cost for Qualcomm to produce an SoC $\underline{\psi}$. These parameters together determine the period profits of Qualcomm and handset makers given a set of smartphones and the corresponding demand and marginal cost shocks. The estimated period profit functions are input to the dynamic model, where I estimate the innovation cost parameters γ in (3) and (4). Because the estimation of the dynamic model relies on the estimated bargaining model, I discuss the identification and estimation of the bargaining model first.

Demand and Smartphone Marginal Cost in the Bargaining Model

Identification

This section discusses the identification of the demand model, the marginal cost function and the bargaining weights. I first explain the identification of the demand. The demand parameters $(\beta, \alpha, \theta, \kappa, \sigma)$ are identified from the joint distribution of the prices, sales and observed smartphone characteristics. The identification may suffer from a sample selection problem because firms choose their product lines. I address this problem with the assumptions in Section 4. The intuition is that firms do not observe demand and marginal cost shocks before the product sets are determined.[25] Under the assumption that product characteristics are independent of demand shocks, the demand parameters are point-identified and can be estimated with BLP instruments.

[24] Consumers may still hold onto their old phones and wait for the release of new phones. The static model does not endogenize these consumer dynamics. Goettler and Gordon (2011) endogenizes consumer beliefs, pricing and innovation with two firms. I leave for future research how to extend the dynamic game to include bargaining and additional firms.

[25] A number of papers in the endogenous product characteristics literature (e.g., Eizenberg (2014); Wollmann (2016); Fan and Yang (2019)) use this assumption to facilitate demand estimation.

I next discuss the identification of the marginal cost parameters λ and the bargaining parameters τ. When the demand for smartphones is identified, the pricing equations in (10) identify the markups and hence the smartphone marginal costs as the difference between observed prices and markups. A smartphone's marginal cost is the sum of the SoC price ψ and costs of other components ω. This total marginal cost is denoted by $\varrho = \psi + \omega$. Neither ψ nor ω is directly observed. Because ω is a function of phone characteristics and λs are the coefficients, I need to first invert ω from ϱ. I rely on Qualcomm's average markup data and a mapping between τ and SoC markup. Intuitively, a higher τ should correspond with a higher average SoC markup in the bargaining equilibrium. The average SoC markup thus identifies τ. Once τ is known, ψ can be identified as the solution to the bargaining first order condition (12).

I now formalize this intuition. The notation here will also help to illustrate the estimation method guided by the identification strategy. I first restrict the bargaining parameter τ to be the same for all Qualcomm-handset maker pairs in the months within a quarter (but could be different across quarters). This restriction is necessary because I observe the average Qualcomm markup aggregated across all handset makers in each quarter.[26] Given an identified demand function and known $\left(\underline{\psi}, \bar{\psi}\right)$, I next make three assumptions that lead to identification.

First, I assume that the bargaining parameter and non-SoC component costs map uniquely to equilibrium handset prices and SoC prices via the bargaining equilibrium and the Nash-Bertrand equilibrium:

Assumption 1. *For every (τ, ω), there exists a unique (p, ψ) that satisfies (10) and (12).*

The mapping is denoted as $\mathcal{H}(\tau, \omega) = (p, \psi)$. If the solutions to (10) and (12) for every τ and ω are unique, the mapping $\mathcal{H}$ is given by this solution. In the case of multiple bargaining or Nash-Bertrand equilibria, the assumption also holds when there is a deterministic equilibrium selection rule known to the researcher, and (p, ψ) is the particular solution to (10) and (12) selected by this rule.[27]

The next assumption links the observed (p, ϱ) with unobserved (τ, ω):

[26] Other papers in the empirical bargaining literature such as Crawford and Yurukoglu (2012) use bargaining-pair specific intermediate prices to estimate pair specific bargaining weights.

[27] The selection rule assumed here is an equilibrium solution method based on the iteration of first order conditions. Similar to Lee and Pakes (2009) and Wollmann (2016), this selection rule is assumed to be part of the model structure. Such iterative solution methods do not guarantee the existence of a solution, but I do not encounter non-existence problems in practice.

Assumption 2. *Every (ϱ, p, τ) corresponds with a unique ψ such that*

$$\mathcal{H}(\tau, \varrho - \psi) = (p, \psi) \tag{13}$$

Such a ψ would be consistent with the observed downstream prices, total smartphone marginal costs and the equilibrium conditions of the bargaining model. This assumption implies that there is a mapping $\tilde{\mathcal{H}}$ such that $\tilde{\mathcal{H}}(\tau, \varrho, p) = \psi$. Therefore fixing ϱ and p, a value of the bargaining parameter τ corresponds with a unique vector of ψ for each market via $\tilde{\mathcal{H}}$. I use $\tilde{\mathcal{H}}$ and data on SoC markup to invert out ω. Specifically, I solve for τ such that the theoretical average markup of Qualcomm SoCs in the quarter starting in month t_0

$$\frac{\sum_{t=0}^{2}\left(\tilde{\mathcal{H}}(\tau, \varrho_{t+t_0}, p_{t+t_0}) - \underline{\psi}\right)' \cdot D_{t+t_0}}{\sum_{t=0}^{2}\tilde{\mathcal{H}}(\tau, \varrho_{t+t_0}, p_{t+t_0})' \cdot D_{t+t_0}} \tag{14}$$

matches the observed quarterly SoC gross margin (described in Section 2).

The last assumption says this τ is unique:

Assumption 3. *(14) is monotonic in τ.*

By finding such a τ_{t_0}, I also find the corresponding $\psi_t = \tilde{\mathcal{H}}(\tau_{t_0}, \varrho_t, p_t)$ for $t = t_0, t_0+1, t_0+2$. $\varrho_t - \psi_t$ identifies ω_t. Regressing ω_t on the corresponding product characteristics gives λ.

Estimation

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 instruments are based on the characteristics of other products of the same handset maker and the products of the competing handset makers.[28] Additionally, I include the four-month lagged exchange rates of the Chinese, Japanese and Korean currencies to U.S. dollars as cost shifters. The estimates of the demand model are presented in Table 4. The characteristics x_j used to construct

[28] This estimation strategy relies on the timing assumption that the demand and marginal cost shocks are realized after the product sets are determined. After controlling for the systematic brand effects, carrier effects and time effects, it is reasonable (though still imperfect) to assume that any product/month-specific shocks are uncorrelated with product characteristics.

the quality index include the screen size,[29] SoC generation, camera resolution, weight and talking time on a full battery. The screen size coefficient is normalized to be 1. The SoC generation fixed effects correspond with Qualcomm's Snapdragon S1 through S4 and comparable products. The omitted generation is for phones that do not use SoCs or use SoCs older than Snapdragon S1. The brand fixed effects of Apple, Samsung and BlackBerry are also included. The demand estimates are reasonably intuitive, with a higher generation, camera resolution, lower weights and longer battery 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, whereas an increase in the screen size by 0.1 inches is equivalent to a price decrease of 11.7 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 estimation are documented in Fan and Yang (2019).

I now discuss how to estimate the marginal cost function (8). Given the estimated demand function and observed prices, the full marginal cost $\omega + \psi$ can be inverted using the first order condition (10). Extra steps are needed to invert out the bargaining parameters τ_t and SoC prices ψ_t, and estimate ω as a function of handset characteristics. I fix Qualcomm's marginal cost of producing an SoC to be $\underline{\psi}$ = $20, and the cost of the non-Qualcomm SoC at the disagreement point to be $\bar{\psi}$ = $60.[30] I base the calibrated value of $\underline{\psi}$ on conversations with fabrication plant engineers and analysts. $\bar{\psi}$ could be directly estimated if I observe in the data that a handset maker uses different SoCs on the same handset. I do not observe such variations during my sample period. I choose a relatively large $\bar{\psi}$ of $60[31] to take into account not only the direct cost of buying the alternative SoC, but also potentially the additional cost of equipping a phone with an SoC the phone was not designed to use. I show in robustness checks that further allowing the handset

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

[30]In Section D, I show that the results are robust if the costs of the non-Qualcomm SoCs and the marginal costs of producing Qualcomm SoCs 5% annually.

[31]According to Woyke (2014), most SoC prices are between $16 and $40.

quality to decrease does not qualitatively change the conclusion. The results later will show that even with a large $\bar{\psi}$, which is disadvantageous for handset makers, the potential harm of raising rival's costs is still limited in the counterfactual vertical integration. To estimate the coefficients in (8), I need to break out the SoC prices ψ. To impute ψ, I rely on the average Qualcomm markup data in its quarterly financial reports and the mapping $\tilde{\mathcal{H}}$ defined in Section 5. To calculate $\tilde{\mathcal{H}}$, I solve for a vector of SoC prices ψ consistent with the observed retail prices by iterating (13) until convergence for every value of (τ, ϱ_t, p_t). The gross margin data are quarterly, and I compute a τ for every quarter by matching (14) with the gross margin in the corresponding quarter.[32] The value of τ in a quarter enables me to invert out ψ for every month in that quarter. 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 SoCs.

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

There may be several concerns with this approach. 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 SoC industry might be expected for two reasons. 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 et al. (2011)). Therefore additional SoC makers may enter to meet the increased demand for Qualcomm alternatives. One may also be concerned with measurement errors in the gross margin data discussed in Section 2. In Appendix D, I re-estimate the model using perturbed gross margin data.

[32] 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.

Sunk Cost of Innovation in the Dynamic Model

The goal is to estimate parameters in (3) through (6). I first use demand estimates to construct handset quality frontiers and the profit functions $\pi_t^Q(s_t), \pi_t^n(s_t)$ defined in Section 4 as inputs 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, the period profits of Qualcomm and handset maker n, $\pi_t^Q(s_t)$ and $\pi_t^n(s_t)$ can be simulated with demand estimates.

However, I do not directly observe the quality of Qualcomm SoCs.[33] Qualcomm's quality frontier of generation g should be interpreted as the highest quality phone that a handset maker can produce with Qualcomm's generation g SoCs. I observe the latest generation of Qualcomm SoCs according to the announcement dates. I argue that with appropriate assumptions on the bounds of the qualities of a generation's SoCs, one can still make inferences about the underlying cost primitives. First, Qualcomm's quality is at least as high as the frontiers of non-Apple handset makers. Therefore the maximum of non-Apple handset maker frontiers, $\max_{n\neq Apple} q_t^n$ forms the lower bound of Qualcomm's quality frontier in t. To bound Qualcomm's quality frontier from above, I make the following assumption:

Assumption 4. *When Qualcomm's latest SoC generation is g in period t, Qualcomm's quality q_t^Q is less than the quality of the first non-Apple handset using generation $g+1$ Qualcomm's SoC.*

As an example, in November 2011 ($t = 35$), the highest quality phone using Qualcomm was Galaxy SII with a Qualcomm Snapdragon S3 SoC and a quality index of 6.68. Because the quality frontier of Qualcomm must be at least as high as any Samsung or HTC phone using an SoC from Qualcomm, I obtain a lower bound, $q_{35}^{Qualcomm} \geq 6.68$. The next generation of Qualcomm's SoC was Snapdragon S4. The first phone adopting Snapdragon S4 was HTC One S with a quality index of 7.42. By Assumption 4, I obtain an upper bound $q_{35}^{Qualcomm} \leq 7.42$.[34]

[33] The SoC generation fixed effects in the quality index are not the qualities of Qualcomm SoCs.

[34] A more restrictive choice is the lowest quality of phones powered by $g+1$ generation SoC instead of the first phone using $g+1$ generation SoC. Such a choice is not consistent with monotonically increasing Qualcomm's quality, because the lowest quality of phones using the new SoC is lower than the previous generation's highest quality.

Identification

I use the estimated period profit functions, handset maker quality frontiers q_t^n, proportions of Samsung's handsets using Qualcomm SoCs $\eta_t^{Samsung}$ and Qualcomm's upper bounds given by Assumption 4 to identify the innovation costs. Like Igami (2017), I obtain the period profits as functions of quality frontiers completely outside the dynamic estimation. These static estimates combined with variations in $q_{t+1}^n - q_t^n$ would identify the innovation cost parameters for handset maker n in (4). (γ_0^n, γ_1^n) increases n's innovation cost and reduce its frequency and size of quality improvements. γ_2^n reduces n's innovation costs. Samsung would innovate faster when $\eta_t^{Samsung}$ is higher.[35] The shape of the quality improvement step size distribution and the normality assumption on ε^n identify σ^n: high σ^n implies that n's month-to-month quality improvements are either 0 or very large.

Although Qualcomm's quality is observed up to a range, the observed handset maker quality improvements and Assumption 4 can still provide meaningful bounds on Qualcomm's innovation cost parameters. Assumption 4 bounds $\left(\gamma_0^Q, \gamma_1^Q\right)$ from below: if $\left(\gamma_0^Q, \gamma_1^Q\right)$ is too small, Qualcomm's innovation cost would be low and its quality frontier would increase too quickly, violating the bounds in Assumption 4. The observed non-Apple handset maker quality frontiers bound $\left(\gamma_0^Q, \gamma_1^Q\right)$ from above: $\left(\gamma_0^Q, \gamma_1^Q\right)$ reduces Qualcomm's innovation, and because non-Apple handset makers cannot innovate above Qualcomm's frontier, these handset maker innovation rates would be low if $\left(\gamma_0^Q, \gamma_1^Q\right)$ is too large. Assumption 4 and the normality assumption on ε^Q also place an upper bound on σ^Q. High σ^Q causes Qualcomm to take large innovation jumps whenever ε^Q is negative (50% probability). Qualcomm's innovation rate then would be too high and violate the bounds in Assumption 4.

Estimation

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 at a monthly discount rate of 0.99 via

[35] These conditions are intuitive in a single-agent model but not directly implied by the market equilibrium. I verify these conditions by perturbing the estimated parameters in Table 24 in the Appendix and find that the innovation rates change in the expected directions.

backward induction. 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. When solving the dynamic game, I assume firms move in the order of 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 SoCs $\left(\eta^{A}=0\right)$ and is not constrained by Qualcomm's quality frontier; the innovation of HTC is constrained by Qualcomm, and HTC always chooses $\eta^{HTC}=1$: the SoCs of all HTC phones are supplied by Qualcomm and their prices are determined in the bargaining equilibrium; Samsung's innovation is also constrained by Qualcomm, but can adjust $\eta^{Samsung}$. 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 Section 7, I further check the sensitivity of the results to the finite horizon assumptions by considering models with longer horizons. 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 (3) and (4), I estimate a firm specific γ_0 and γ_1. I restrict $\sigma^{Apple}=\sigma^{Samsung}=\sigma^{HTC}\equiv\sigma^{handset}$ and estimate a different $\sigma^{Qualcomm}$, leaving a total of 11 parameters to estimate. There are a total of $T=51$ months of data. I fix the qualities in month 1 and use quality choices of the next $T-1$ periods for estimation. I use a computationally simple estimator in Shi and Shum (2015) to find the 95% confidence set of the identified set. Denote the equality moments as g^{e} and inequality moments as $g^{ie}\leq 0$. The confidence set is defined as

$$CS_T=\left\{\theta\in\Theta\,:\,g^{ie}\leq 0,g^{e\prime}Wg^{e}\leq\chi^2_d\left(0.95\right)/\left(T-1\right)\right\},\tag{15}$$

where W is the weighting matrix and $\chi^2_d\left(0.95\right)$ is the 95% quantile of χ^2 distribution of d degrees of freedom. d is the number of equality constraints in g^{e}. Denote the upper bound of Qualcomm's quality observed in each period t as ρ_t. I consider the following two sets of stationary equality moments and one inequality restriction:

1. mean innovation rates, defined as $\left(q_T-q_1\right)/\left(T-1\right)$ for Apple, Samsung and HTC;

2. mean proportion of Samsung products using Qualcomm SoCs, $\sum_{t=2}^{T}\eta_t/\left(T-1\right)$.

3. $q_t^{Q}<\rho_t$ by Assumption 4.

I use $q_{t,r}^{(\cdot)}$ and R to denote the quality in simulation r and the total number of simulations. To create a stationary inequality moment, I subtract the highest non-Apple smartphone quality from Qualcomm's quality and consider the restriction

$$q_t^Q - \max\left(q_t^{Sam}, q_t^{HTC}\right) < \rho_t - \max\left(q_t^{Sam}, q_t^{HTC}\right).$$

The actual inequality constraint used in estimation is

$$\sum_{r=1}^{R}\sum_{t=2}^{T}\left(q_{t,r}^{Q} - \max\left(q_{t,r}^{Sam}, q_{t,r}^{HTC}\right)\right)/\left((T-1)\,R\right) \leq \sum_{t=2}^{T}\left(\rho_t - \max\left(q_t^{Sam}, q_t^{HTC}\right)\right)/\left(T-1\right). \quad (16)$$

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 several reasons. First, these moments are closely related to the identification of the mean innovation costs. For example, a high γ_0 or γ_1 for the handset makers will imply a slow innovation and cause deviations in the first set of equality moments. Furthermore, if γ_0 or γ_1 specific to Qualcomm is large, Qualcomm's innovation will be slow, which also slows down the innovations of Samsung and HTC. If Qualcomm's γ_0 or γ_1 is low, Qualcomm innovates more quickly and will violate the inequality constraint. The remaining Qualcomm usage parameter γ_2 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 model,[36] whereas 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 misspecification (Chernozhukov et al. (2007); Andrews and Soares (2010); Romano et al. (2014)) involve a bootstrap or re-sampling step to compute the confidence set and are 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

[36]In particular, the model is unable to fit the standard deviation of the innovation rates of Apple and Qualcomm, which innovate more infrequently than Samsung or HTC. Samsung had two flagship series, Galaxy S and Note, and several variants of different qualities were released several times a year (Fig.2), but Apple released one generation of new iPhones a year.

in Shi and Shum (2015).

The estimated 95% confidence set consists of a set of vectors of parameters that satisfy (15). 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 innovation actions, we can interpret the parameter estimates in terms of "semi-elasticities". For example, increasing quality by 0.1 unit increases the innovation cost by 1.6 to 1.7 times for Apple. Using Qualcomm SoCs on more handsets reduces the innovation cost for Samsung. In Figure 3, I plot the brand-fixed effect adjusted quality frontiers ($q_t^n + \frac{\theta_n}{\bar{\beta}_0}$) in data and simulation. The simulated quality frontier is the average of 960 simulated paths based on a random draw of parameters in the confidence set.

I use simulations to examine whether the estimates of innovation costs are sensible by comparing the estimates with accounting measures of R&D and operating expenses. To quantify the costs of innovation, I use a procedure described in Appendix C to sample a representative set of points from the confidence set to simulate the dynamic model. At each vector of parameter values in this set, the model is simulated 960 times for the sample period; the total investment is discounted and summed across periods in each simulation and then averaged across simulations. Table 7 reports the ranges of this average for Apple, Samsung, HTC and Qualcomm across sampled points in the confidence set. The reported ranges approximate the 95% confidence intervals of the expected total investment during the sample period. To examine whether these figures are sensible, I compare the operating expenses[37] in HTC's financial reports[38] with the total investment implied by the model. The interval estimates of the expected total investment by HTC are between 3.07 and 4.75 billion dollars, with the model assumption that the US market accounts for a constant share of the world market, so that the innovation costs are also of the same proportion of the "true" innovation costs of HTC on a global scale. According to HTC's annual reports, 48% of HTC revenues came from US, and therefore the 95% confidence interval of the expected total HTC investment scaled to the global level is from 6.4 to 9.9 billion dollars. In comparison, the discounted HTC operating expenses[39] totaled 6.83 billion dollars during the period. The simulated investment level matches the HTC accounting figures in scale.

[37]R&D, selling, general and administrative costs but not manufacturing costs of the goods sold, in the accounting sense.

[38]Apple, Samsung and Qualcomm have major operations outside the SoC and smartphone industries, and their accounting costs are less relevant.

[39]The reported figures are discounted by an annual rate of $0.99^{12} = 0.89$.

Investment data can be informative about whether the assumption of incomplete contracts is valid. 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. 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 innovation costs of HTC would be lower than the actual investment. Specifically, the null hypothesis of $\varsigma = 0$ is rejected if the observed investment is much higher than the model predicted range of investment. If higher quality firm specific investment data were available, I could formally estimate ς.

6 Counterfactual Simulation

I use the estimated model to simulate two approaches that address the potential under-innovation problem in vertically separated industries. The first counterfactual considers a hypothetical vertical merger between Qualcomm and HTC. This merger was not likely and did not happen, but the simulation allows me to measure the impact of various countervailing economic forces in vertical integration. The second counterfactual assesses the effect of an upstream R&D subsidy for Qualcomm. I examine whether the faster innovation of Qualcomm can stimulate additional downstream innovations, and whether the increase in the total social surplus exceeds the amount of the subsidy.

Vertical Integration

In this counterfactual, I examine how innovation rates and welfare would be different if Qualcomm were integrated with HTC. HTC is a natural choice for this simulation because of its high dependence on Qualcomm SoCs. Moreover, Apple, the unconstrained handset maker, and Samsung, which can flexibly adjust the proportion of its handsets using Qualcomm SoCs, resemble typical downstream competitors to a vertically integrated firm. A vertical merger between Qualcomm and HTC allows the integrated firm to internalize the innovation complementarity and likely would increase innovation. Whether Samsung and consumers would be harmed by a vertically integrated Qualcomm is of particular interest. On one hand, the faster innovation of Qualcomm would increase the innovation of Samsung by increasing the quality or frequency of new SoC releases. On the other hand, Qualcomm may increase the prices of the SoCs supplied to Samsung, which may in turn increase the prices of Samsung's phones.

The integrated HTC obtains SoCs at the marginal cost $\underline{\psi}$, and the prices of the SoCs for Samsung maximize the following Nash product:[40]

$$\left[\pi_t^Q\left(\boldsymbol{\psi}_{Samsung,t},\boldsymbol{\psi}_{-Samsung,t}\right)+\pi^{HTC}\left(\underline{\psi},\boldsymbol{\psi}_{-HTC,t}\right)-\tilde{\pi}_t^Q\left(\boldsymbol{\psi}_{-Samsung,t}\right)-\tilde{\pi}^{HTC}\left(\underline{\psi},\boldsymbol{\psi}_{-HTC,t}\right)\right]^{\tau_t}\cdot$$
$$\left[\pi_t^{Samsung}\left(\boldsymbol{\psi}_{Samsung,t},\boldsymbol{\psi}_{-Samsung,t}\right)-\tilde{\pi}_t^{Samsung}\left(\boldsymbol{\psi}_{-Samsung,t}\right)\right]^{1-\tau_t}, \tag{17}$$

Compared with the Nash product in (11) where Qualcomm is independent, the first line in (17) includes additional terms accounting for the likely *increase* in the surplus of HTC if Samsung switches to the fringe SoCs (which entail higher marginal costs for Samsung handsets). At the vector of prices that maximize (11) (the Nash product where Qualcomm is separated), if it is profitable for the integrated Qualcomm to increase the SoC prices to Samsung, the combined increase in Qualcomm and HTC surpluses ($\pi_t^Q+\pi_t^{HTC}$) must be proportionally larger than the loss in Samsung profit $\pi_t^{Samsung}$ after being weighted by the respective bargaining weights, τ_t and $1-\tau_t$. Therefore the effect of "raising rival's cost" in the bargaining model is similar to Salop and Scheffman (1983) and Krattenmaker and Salop (1986), where an increase in input prices changes the downstream prices, and whether the integrated firm finds it profitable to increase the input prices depends on the relative changes in the sales of the integrated and independent downstream firms. Additionally, the integration eliminates the double marginalization between Qualcomm and HTC, and HTC sets retail prices to maximize the joint profits from HTC phones sales and Qualcomm's SoC sales. I use $\pi^{VI}(s)$ to denote the joint profit from the integrated Qualcomm's SoC sales and the integrated HTC's handset sales.

The integrated firm invests to maximize the joint value function, internalizing the effect of HTC's innovation on Qualcomm and vice versa. In all simulations, I make the following assumptions such that the comparison with the non-integration scenario is fair: the "Qualcomm division" of the merged firm still moves first after observing its private shock, followed by Apple, Samsung and the "HTC division" of the merged firm. Use $V^{VI}(s)$ to denote the joint value function of the two

[40]The first order conditions are in Appendix A.

divisions. Consistent with Section 3, the value function is defined as the present discounted value at the beginning of a period, before firms receive their payoffs. The new dynamic programming problem for the Qualcomm division of the merged firm is

$$\max_{a^Q} \left\{ -C^Q \left(a^Q, \varepsilon_t^Q \right) + \delta E \left(V_{t+1}^{VI} \left(s_{t+1} \right) \middle| a^Q, s_t \right) \right\}, \tag{18}$$

and the HTC division

$$\begin{aligned} \max_{a_q^{HTC}} & - C^{HTC} \left(a_q^{HTC}, \varepsilon_t^{HTC} \right) \\ & + \delta V_{t+1}^{VI} \left(s_{t+1} \left(s_t, a_t^Q, a_{qt}^{Apple}, a_{qt}^{Samsung}, a_{\eta t}^{Samsung}, a_q^{HTC} \right) \right). \\ s.t. q_t^{HTC} & + a_q^{HTC} \leq q_{t+1}^Q. \end{aligned} \tag{19}$$

In (18), the expectation is taken over the Qualcomm division's belief about the actions of Apple, Samsung and the HTC division. The HTC division's action is a random variable to the Qualcomm division, because HTC moves later and the innovation cost shock of HTC has not yet realized. The Bellman equation for the joint firm is

$$\begin{aligned} V_t^{VI} \left(s_t \right) = \pi_t^{VI} + E_{\varepsilon_t^Q, \varepsilon_t^{HTC}, a_q^{Apple}, a_\eta^{Samsung}, a_q^{Samsung}} & \left[-C^Q \left(a_t^{Q\star}, \varepsilon_t^Q \right) \right. \\ \left. -C^{HTC} \left(a_{qt}^{HTC\star}, \varepsilon_t^{HTC} \right) + \delta V_{t+1}^{VI} \left(s_{t+1} \left(s_t, a_t^{Q\star}, a_q^{Apple}, a_\eta^{Samsung}, a_q^{Samsung}, a_{qt}^{HTC\star} \right) \right) \right], \end{aligned} \tag{20}$$

where the expectation is taken over $\varepsilon_t^Q, \varepsilon_t^{HTC}$, and the Qualcomm division's belief about the actions of Apple and Samsung. $a_{qt}^{HTC\star}$ is defined as the solution to (19) and is a function of s_t, ε_t^{HTC}, and the actions of the Qualcomm division, Apple and Samsung. In the PBE, the beliefs are consistent with the true action probabilities. The assumption above keeps the information structure the same as the non-integration scenario to isolate the effect of coordination.[41]

I conduct four sets of simulations, corresponding with the four columns in Table 8. For each

[41] Alternatively, one could assume that Qualcomm and HTC simultaneously observe their respective shocks and move, but such a counterfactual would contain the effects of (a) innovation coordination, (b) the change in the sequence of the move and (c) the change in the information structure (Qualcomm does not know HTC's private shock in the non-integration scenario). (a) is the main economic effect due to the vertical integration, and the latter two effects are byproducts of the auxiliary assumption of sequential move to maintain tractability. I therefore assume the integrated Qualcomm and HTC sequentially decide on innovation to focus on the effects in (a).

set, I simulate $R = 240$ paths of innovations. Below I describe each set of simulations:

1. Non-integration. I simulate the estimated model.

2. I hold fixed the innovation paths and Samsung's Qualcomm usage ($\eta^{Samsung}$) in column (1), and for each path, I recompute the prices and welfare under Qualcomm and HTC integration. The comparison between these two sets reveal the direct effect of vertical integration on prices.

3. Qualcomm and HTC price their products as if they were still separate, but the two firms pool their profits when making dynamic investment decisions: the investment decisions of Qualcomm and HTC are solutions to Eq. (18), (19) and (20), with π^{VI} replaced by $\pi^{Q} + \pi^{HTC}$, where π^{Q} and π^{HTC} are profits of the non-integration scenario defined in Section 4. Comparing this scenario with the second one, I turn off the channel of vertical integration changing the pricing incentives (the focus of the second simulation) and focus on the direct effect of vertical integration on investment coordination. This setup is similar to the "research consortium" in some industries (Branstetter and Sakakibara (2002)).

4. I simulate the full vertical integration scenario, where Qualcomm and HTC coordinate both pricing and investment.

I simulate the first 36 periods to guard against the effects of the finite horizon assumption.[42] All dollar figures are discounted to January 2009.

Table 8 reports the summary of results corresponding with the four sets of simulations. The end points of the intervals are the maximum and minimum of the simulation outcomes across points sampled from the confidence set according to the procedure in Appendix C. I report the average increase in qualities, sales-weighted average SoC prices, sales-weighted average retail prices, the proportion of Samsung handsets using Qualcomm, consumer surpluses, producer surpluses, total welfare and investment. I first summarize the main findings:

1. Comparing columns (1) and (4), I find

   (a) vertical integration increases the innovation of both the upstream Qualcomm and the downstream firms that rely on Qualcomm SoCs; the change in Apple's innovation rate

[42]Simulating the full 51 periods produces qualitatively similar results, as shown in Section 7. Focusing on the first 36 periods reduces the effects of the assumption on what happens in the last period.

is comparatively much smaller; the 95% confidence set of the proportional change of HTC's innovation is $[14\%, 20\%]$,Qualcomm $[13\%, 35\%]$, Samsung $[9\%, 22\%]$ and Apple $[1.3\%, 2.7\%]$;

   (b) the consumer surplus and total surplus increase; the mean increases are 1.6 and 2.6 billion dollars;

   (c) despite having to pay higher prices for Qualcomm SoCs, Samsung is better off with the vertical integration: Samsung innovates faster and its surplus increases by about 0.55 billion dollars.

2. Comparing columns (1) and (2), I show that Qualcomm raises the average SoC price to Samsung by about \$1. This price increase is caused by the changed pricing incentive alone, because the state variable evolution of each path is held the same as column (1). The pass through to the average retail price is less than 1: Samsung's average retail price increases by \$0.2. At the same time, the HTC retail price decreases by \$13, partly due to the elimination of double marginalization.[43]

3. Comparing columns (1), (3) and (4), I decompose the gains from vertical integration (column (1) to column (4)) into two parts: investment coordination (column (1) to column (3)) and changed pricing incentive (column (3) to column (4)).[44] The investment coordination is the main driver of the innovation increase. The mean increase of Qualcomm innovation from (1) to (4) is 0.019. From (1) to (3) the mean increase is 0.018. Therefore the channel of investment coordination accounts for $\frac{0.018}{0.019} = 95\%$ of the total increase of Qualcomm innovation, and the channel of the changed pricing incentive accounts for 5%. The changed pricing incentive has a larger impact on consumer and total surpluses, accounting for 18.5% and 11.8% of the respective increases from (1) to (4).

[43] Vertical integration eliminates double marginalization, which tends to reduce the integrated HTC's handset prices. Vertical integration also changes the pricing of HTC handsets: HTC sets retail prices to maximize the joint profits from Qualcomm's SoC sales to Samsung and HTC handset sales. The latter effect is likely to decrease HTC and Samsung retail prices: the HTC and Samsung prices tend to be strategic complements, and the integrated HTC has incentive to reduce prices to expand Samsung sales, forcing Samsung to reduce retail prices in equilibrium and increase the unit sales of Samsung handsets (and the unit sales of the Qualcomm SoCs in these handsets). As a result, just 20% of the SoC price increase is passed through to the Samsung retail price.

[44] Alternatively, I can label the difference between column (1) and column (2) as the effects of changed pricing incentive, and the difference between column (2) and column (4) as the effects of investment coordination. The results are not identical but similar.

I next examine Samsung's innovation in the new equilibrium with the vertically integrated Qualcomm. Samsung innovates faster and uses more Qualcomm SoCs, taking advantage of the new SoCs that become available faster and the innovation cost reduction from a higher η, despite having to pay more for Qualcomm SoCs each period.[45] Furthermore, I show that Samsung's innovation becomes more frequent and the average step size is larger: in Fig. **??**, I compute the innovation probabilities for each period and each observed state in simulation and average the probabilities across all states; I similarly plot the average innovation step size conditional on innovation.

I also examine how these summary statistics vary over time in Fig.4, 5, 6, 7 and 8. For the clarity of the plots, I use the average of the simulated paths for each scenario. I leave out the scenario corresponding with the Table 8 column (2) (which has same paths as in column (1), the non-integration case) and examine the time series variations in quality indices, profits, prices and investment corresponding with (1), (3) and (4), which are labeled "no-integration", "investment coordination" and "VI". The time series plots suggest that over time, the effect of VI becomes more pronounced: towards later periods, vertical integration increases HTC and Samsung qualities more; Apple's quality is slightly higher and its profit slightly lower; the welfare gains are also higher in later periods.

Finally, the plots also show cyclical patterns within a year as a result of the carrier-time fixed effects in the demand and marginal cost functions. The repeating patterns provide some justification for the assumption that firms have perfect foresight for π_t.

Vertical Integration with Royalties

Given the vertical integration's large positive effect on Qualcomm and HTC's innovation and surplus, the obvious puzzle is why Qualcomm remains vertically separated. As discussed in Section 2, Qualcomm might risk losing the patent revenues if Qualcomm remained vertically integrated. To assess whether the patent revenues can explain Qualcomm's decision to be vertically separated, I simulate what would happen to Qualcomm and HTC's surplus if Qualcomm and HTC are merged and Qualcomm no longer has patent revenues. I make additional assumptions to calibrate handset wholesale prices in order to impute the patent revenues to Qualcomm. I then incorporate the patent

[45] Table 8 shows that the effect of "raising rival's costs" and higher qualities of Samsung handsets both contribute to higher SoC prices to Samsung with vertical integration.

revenues in the Qualcomm profit function, estimate the innovation costs and simulate the outcome with a Qualcomm that is vertically integrated with HTC but does not collect patent revenues. 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 1710 dollars. A wireless carrier whose main businesses are wireless and data services (like T-Mobile) typically has a gross margin of 50% according to their financial reports. Assuming that the wholesale prices of the phones are the 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 profit function of handset maker n becomes

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

and Qualcomm's profit function is modified to include the additional revenues from the patent royalties. At the disagreement point in the bargaining game, a vertically separated Qualcomm continues to earn royalties from the handset maker even if the handset maker switches to an alternative SoC, but a vertically integrated Qualcomm negotiates SoC prices in the same way as in (17). I assume that Apple's royalty rate is 2%, Samsung 3% and HTC 5% (Arghire (2009); Clark (2009)). I re-estimate the model, and report the simulation results in Table 9. Had Qualcomm lost the patent revenues, the joint surplus of Qualcomm and HTC would in fact decrease, which lends support to the argument that Qualcomm is better off remaining independent and keeping the patent revenues.

Another explanation for the observed vertical separation is that other SoC makers may seek to replace a vertically integrated Qualcomm. I argue that as long as these new entrants do not overtake Qualcomm and lead the SoC frontier,[46] the estimated effect of vertical integration above is robust. I model this possibility as a 10% decrease in the cost of alternative SoC $\bar{\psi}$ at the disagreement point in the Nash product when simulating the counterfactual industry evolution with the vertically integrated Qualcomm and HTC. Table 10 shows that the effects of vertical integration are similar to the main specification.

[46]Taking the lead over Qualcomm would be a substantial undertaking. Major designers such as Samsung's SoC division did not succeed during the sample period.

Finally, I show that even after taking into account the patent revenues, Qualcomm does not fully internalize the complementary innovations of downstream firms. I simulate and compare the innovation rates under vertical separation and integration, where Qualcomm collects patent revenues in both cases. The simulation results in Table 13 show that the positive effects of vertical integration are still sizable and qualitatively similar to the main specification in Table 8. Explicitly modeling the modem supply relationship further complicates the bargaining model, but the economic effect is similar to the patent revenues. I offer additional discussions in Section 8.

Upstream Subsidy

Government R&D subsidies are often justified by the argument that the social returns of R&D (including spillovers) are often much larger than private returns (Griliches (1992); Hall (1996)). In this section, I use the empirical model to quantify to what extent a hypothetical upstream subsidy can resolve the under-innovation problem in vertically separated industries. A strong case for subsidizing a GPT provider is that its faster innovation may stimulate the innovations of downstream firms. This question is particularly relevant in the current trade dispute between US and China. A main obstacle to reaching an agreement is the Trump administration's insistence for China to stop subsidizing high tech firms such as those in the semiconductor industry (Zhai (2018)). The two Chinese firms caught in the crossfire, Huawei and ZTE, both have their smartphone SoC initiatives.

I examine the impact of a subsidy to Qualcomm on innovation and welfare. I consider four scenarios, where Qualcomm's innovation cost is subsidized by ζ =10%, 15%, 20% and 25%. In each scenario, the cost of Qualcomm innovation is $(1-\zeta)\cdot C^Q\left(a^Q,\varepsilon_t^Q\right)$, and the government subsidy is $\zeta C^Q\left(a^Q,\varepsilon_t^Q\right)$ conditional on a Qualcomm innovation. Consistent with Section 6, I simulate the industry evolution for 36 months and show the results in Fig. 9. The left graph shows the change of equilibrium innovation rates, and the right panel compares the amount of the subsidy with the change in consumer surplus, total surplus, and the total private investment (both Qualcomm and downstream firms). The results show that subsidies are effective at increasing Qualcomm's innovation, and a 10% subsidy corresponds with a 15% increase in innovation. This subsidy also increases Samsung's innovation by 11%. The increase in HTC's innovation increases less (1.3%), and Apple's innovation rate decreases by about 2%. The subsidy improves welfare: the total increase in consumer welfare alone is about 6 times the amount of the subsidy. Finally, the increases in private investment are larger than the subsidies across all four scenarios.

In comparison with the larger increase of HTC's innovation in the vertical integration counterfactual, this exercise shows that an upstream subsidy can be effective at stimulating the innovation of some downstream firms, but does not fully resolve the innovation externality. The reason for the small increase of HTC's innovation is that HTC is mostly not "constrained" by Qualcomm's technological ceiling in the absence of the subsidies: without any subsidy, on average HTC's quality coincides with Qualcomm's quality frontier in 0.57 months, compared with Samsung's 5.98 months (out of the 36 months simulated). A 10% Qualcomm subsidy would decrease the number of such days to 4.69 for Samsung, a 22% decrease.

7 Robustness Analysis

Technology Road Maps

In the semiconductor industry, it is often customary for the chip makers to publish guidance on future technology developments. Bresnahan and Trajtenberg (1995) points out that such "road maps" are one way for vertically separated firms (especially in the semiconductor industry) to partially coordinate innovation, although its usefulness for coordination is limited when the technology growth is rapid and hard to predict, as is the case of the smartphone industry. For example, Apple caught Qualcomm off-guard when Apple introduced 64-bit processors, and Qualcomm likely moved up the release of its own 64-bit SoC in response (Spence (2016)). In this section, I consider the following question: how would vertical integration affect downstream innovations if the upstream innovation path is known and fixed? This exercise will quantify the importance of including the endogenously innovating upstream firm.

For this exercise, I assume that Qualcomm's innovation path coincides with the upper bound I impose in Assumption 4, i.e., the Qualcomm frontier is equal to the quality of the first handset using the next generation Qualcomm SoCs. I find that using a lower quality path gives similar results. The state variable consists of $\left(t, q^{Apple}, q^{Samsung}, \eta^{Samsung}, q^{HTC}\right)$. The difference from the model in Section 3 is that Qualcomm future qualities are known and thus absorbed in the time stamp t in the state variable, similar to the time fixed effects in the demand and marginal cost functions.

Qualcomm negotiates prices but does not endogenously innovate. Qualcomm and downstream handset makers still set SoC prices via Nash bargaining. I then re-estimate the innovation cost of the downstream handset makers. In the counterfactual analysis, the vertical integration changes the pricing incentives in the same way as described in Section 6. In every period, Apple moves first, followed by Samsung and HTC. With vertical separation, the respective Bellman equations are similar to those in Section 3, less the terms involving a_t^Q.

In the case of vertical integration, HTC's optimization problem is

$$\begin{aligned}
&\max_{a_q^{HTC}} - C^{HTC}\left(a_q^{HTC}, \varepsilon_t^{HTC}\right) \\
&\qquad + \delta V_{t+1}^{VI}\left(s_{t+1}\left(s_t, a_{qt}^{Apple}, a_{qt}^{Samsung}, a_{\eta t}^{Samsung}, a_q^{HTC}\right)\right), \\
&s.t. q_t^{HTC} + a_q^{HTC} \leq q_{t+1}^Q.
\end{aligned}$$

The Bellman equation is

$$\begin{aligned}
V_t^{VI}(s_t) = \pi_t^{VI} + E_{\varepsilon_t^{HTC}, a^{Apple}, a_q^{Samsung}, a_\eta^{Samsung}} &\left[-C^{HTC}\left(a_{qt}^{HTC\star}, \varepsilon_t^{HTC}\right)\right. \\
&\left.+\delta V_{t+1}^{VI}\left(s_{t+1}\left(s_t, a_q^{Apple}, a_q^{Samsung}, a_\eta^{Samsung}, a_{qt}^{HTC\star}\right)\right)\right],
\end{aligned}$$

and the expectation is taken over ε_t^{HTC} and HTC's belief about Apple and Samsung's actions.

I report the results of vertical integration in Table 11. The changes of Samsung and HTC's innovation rates are more moderate: their innovations increase by about 2% and 7% on average, compared with the 15% and 17% increases if Qualcomm innovation is not fixed (the main specification). The vertical integration overall still improves welfare. The exercise highlights that the endogenous change in upstream innovation could potentially account for more than half of the gains from vertical integration.

Finite Horizon Assumption

As a modeling device to simplify computation, I assume that the dynamic game ends 6 months after the end of the data (51 months in the data; the horizon length is 57 periods),[47] and I focus

[47] Zheng (2016) alternatively assumes that firms consider the profits of the next several periods instead of taking into account the discounted future profits over the entire horizon of the game.

on how the market structure or policy changes affect the outcomes in the first 36 months of the game to guard against the effects of the assumption on the last period. Through two exercises I show that the finite horizon assumption does not appear to drive the results. First, I show that simulating all 51 periods does not qualitatively change the results of the vertical integration or upstream subsidy counterfactual simulations. The vertical integration results are in Table 12 and the upstream subsidy results are in Fig. 10. Secondly, as I increase the length of the horizon from 57 months to 63 months (ending 12 months after the end of the data), the results remain qualitatively stable. For brevity, I report in Fig. 11 the mean increases of innovations due to VI and the mean increases of innovations due to a 15% Qualcomm innovation cost subsidy over 7 different horizon lengths (57 to 63 periods). I also report in Table 14 and Figure 12 the effects of VI and the effects of additional levels of the subsidies for the horizon length of 63 months.

Alternative Market Size Definition

The main specification in Section 4 assumes a fixed market size, and the increasing popularity of smartphones is captured through the quality indices and carrier-time fixed effects. One may still be concerned that the fixed effects are insufficient in this non-stationary environment. In this section, I consider an alternative market size definition based on the unit sales of smartphones and feature phones, and the outside share is the proportion of the unit sales of the feature phones. Fig. 13 documents the monthly unit sales of all phones and of smartphones over time. The figure shows that smartphones gradually overtook the entire mobile phone market during the sample period. I re-estimate the demand using the market share data based on the market size defined as the total unit sales of all phones in a month. The market size thus changes from month to month. Firms are assumed to know the future market sizes, and the market size as a state variable is absorbed in the time stamp t, similar to the time fixed effects in the demand and marginal cost functions. I re-estimate the dynamic model and simulate the counterfactuals. Table 15 reports the effects of the vertical merger. Fig. 14 shows the effects of the Qualcomm subsidies. The proportional changes of innovations and surpluses are comparable to and slightly larger than the main specification, which shows that the fixed effects in the demand and marginal cost functions did a reasonable job capturing the non-stationarity in data.

8 Discussion

Before concluding, I provide a discussion on how the model in this article accommodates the unique features of the SoC and smartphone industries discussed in Section 2. Most importantly, FTC claimed that Qualcomm employed a "no license-no chip" policy, leveraging its monopoly power in the modem market to extract licensing revenues from the handset makers. the complaint against Qualcomm stated that the handset makers (including major handset makers such as Apple and Samsung) often had no recourse but to pay the royalties Qualcomm demanded, because alternative suppliers of modem chips lacked either the quality or the capacity.

To account for the conduct of Qualcomm in the modem and licensing markets, I first provide a robustness analysis in Section 6 where Qualcomm chooses the timing and the extent of improvement to the SoCs based on the future profits from the SoCs and licensing revenues. Although for tractability reasons, I do not model a separate bilateral bargaining game for pricing the modems sold by Qualcomm to Apple or Samsung, the calibrated royalties appear to be similar to the actual combined profits for Qualcomm from the royalty payments and thin modem sales.[48]

Furthermore, I argue that the pricing model of the SoC is reasonable in the presence of the "no license-no chip" policy. There are two key assumptions in the expanded model that takes into account the royalties in Section 6. First, I assume that the royalty rates are exogenous and do not change at the disagreement point. One justification is that royalty rates are subject to the FRAND rule and much more rigid than the chip prices bargained over in the short-term.[49] Secondly, I assume that a handset maker switches to non-Qualcomm SoCs at the disagreement point but the handset maker continues to pay Qualcomm royalties. This assumption follows from the fact that although MediaTek, NVIDIA, Samsung and several other chip makers were capable of building the application processors and the SoCs (such an SoC would have the application processor, GPU and other components but not the modem), any handset maker that purchased these SoCs still

[48]For example, the FTC v. Qualcomm case showed that Qualcomm received about $7.5 per iPhone in royalties (after taking into account various rebates in 2007, 2011 and 2013). In addition, as a back-of-the-envelope exercise, given a 50% gross margin (QCT financial statement), the margin on a thin modem is about $9 (Chafkin and King (2017)). Therefore the marginal profit for Qualcomm per iPhone is about $16.5. In comparison, the calibration exercise uses, at the median, $981 as the basis of the royalty charge (iPhone) with a 2% rate, which amounts to $19.6 as the net profit per iPhone for Qualcomm.

[49]Qualcomm's royalty rates were likely based on historical precedents: "Qualcomm entered five CDMA license agreements before 1993, when the CDMA standard was adopted, and that Qualcomm's royalty rates varied from 4% to 6.5%." Page 177, Findings of Facts and Conclusions of Law, FTC v. Qualcomm, Case No. 17-CV-00220-LHK.

needed to purchase the thin modems from Qualcomm, which in turn could still demand royalties by threatening to withhold the supply of the thin modems.

A related issue is whether one should be concerned with the capacity and quality of the third-party suppliers of SoCs. Although capacity constraint was a main reason handset makers were not able to find viable alternatives to Qualcomm's modems, there were other SoC producers with large capacity. For example, MediaTek was a main producer of SoCs (without the modems, which handset makers needed to purchase separately from Qualcomm) for the high-volume, low-end smartphone producers in Asia (Shih et al. (2010)). However, using an alternative SoC to the original specification of a phone might lower the quality of the phone. I separately address this concern in Appendix D by estimating an alternative pricing model where handset qualities decrease at the disagreement point with Qualcomm, and the results do not qualitatively change.

Lastly, one may be concerned that Qualcomm's use of market power in the modem market creates a bias in the estimation, because Qualcomm could offer handset makers rebates on royalties in exchange for them to use Qualcomm SoCs that include its modems. This issue does not bias the estimates of the qualities of phones or SoCs, which are based on the characteristics of phones and not SoC brands. In the specification of the dynamic model and the innovation cost functions, I deal with this issue by estimating the parameter $\gamma_2^{Samsung}$. The estimates suggest that Samsung can reduce its innovation cost by committing to using Qualcomm SoCs on more handsets in the next generation of Samsung's smartphones.[50]

9 Conclusion

This article estimates a new model that combines bilateral bargaining with dynamic upstream and downstream innovations for the SoC and smartphone industries. Using the estimated model, I simulate the counterfactual experiments of vertical integration and an upstream subsidy. In the first counterfactual, I consider a hypothetical merger of Qualcomm and HTC. The vertical integration spurs the innovation of all firms and improves welfare. The investment coordination between the merged firms drives most of the gains in equilibrium. The second counterfactual shows that subsidizing Qualcomm stimulates the innovations of Qualcomm and the downstream

[50]However, this lump sum rebate is assumed to be a structural function of Samsung's choice of η instead of a negotiated outcome. I do find the counterfactual results are robust to local perturbations of this parameter.

handset makers that rely on the SoCs from Qualcomm, generating welfare gains greater than the amount of the subsidy. These results are robust to a number of alternative model specifications and institutional features.

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Appendix (For Online Publication)

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

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

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

The first order condition of the bargaining game is

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

where Θ and Φ are given by the following:

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

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

where in vector and matrix notation,

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

where L^Q is a binary matrix such that $L^Q_{i,j} = 1$ if i, j both use Qualcomm SoCs, 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's SoC:

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

and $\tilde{\boldsymbol{D}}_Q(n)$ corresponds with the vector of demand for Qualcomm SoCs 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 of the bargaining equilibrium becomes

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

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

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

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

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 negotiate SoC prices with non-integrated downstream rivals but not with the integrated downstream division.

B Product Set Simulation

Each handset maker sells multiple smartphones through multiple carriers. I abstract from endogenizing the product characteristics because of the computational difficulty.[51] I instead assume that the set of products $J(s)$, the set of products using Qualcomm SoCs $J_Q(s)$, the demand shocks ξ, the marginal cost shocks $\varkappa$ and the bargaining weights τ are independent of each other and i.i.d across time conditional on the state $\left(q^Q, q^{Apple}, q^{HTC}, q^{Sam}, \eta^{Sam}\right)$, and the expected profit for Qualcomm is

$$\pi_t^{Qualcomm}(s) = E_{J_Q(s),\xi,\varkappa,\tau}\left[\sum_{j\in J_Q(s)}\left(\psi_j^\star - \underline{\psi}\right)D_{jt}^\star(\xi,\varkappa,\tau,J(s))\right],$$

and the expected profit for handset maker n in period t is

$$\pi_t^n(s) = E_{J(s),\xi,\varkappa,\tau}\left[\sum_{j\in J_n(s)}\left(p_j^\star(\xi,\varkappa,\tau,J(s)) - mc_j\right)D_{jt}^\star(\xi,\varkappa,\tau,J(s))\right],$$

where $\psi^\star$, $p^\star$ and $D^\star$ are equilibrium SoC prices, retail prices and demand given a set of products, the corresponding demand shocks and marginal cost shocks. The expectation is taken over the random product sets $J(s), J_Q(s)$ and the shocks. In practice, I simulate 50 draws of product sets and shocks, separately calculate the Nash-Bertrand equilibrium profits for each draw of the product set and shocks, and use the respective average profits for π_t^Q and π_t^n. I assume that $J(s)$, ξ, $\varkappa$ and τ are independent conditional on s. I simulate $J(s)$, ξ, $\varkappa$ and τ with their estimated empirical distributions under the independence assumption. For ξ, $\varkappa$ and τ, I directly re-sample from the inverted ξ, $\varkappa$ and τ (from the estimation). Below I describe how to simulate $J(s)$.

For the expected profit in period t with the state $s = \left(t, q^Q, q^{Apple}, q^{HTC}, q^{Sam}, \eta^{Sam}\right)$, I start with Apple. I first uniformly sample a period $t_A \in \{1\ldots 51\}$. Let the highest quality of iPhones in t_A be $\bar{q}_{t_A}^A$. I then adjust the quality of every iPhone (a model type-carrier pair, such as iPhone 4S-ATT) in t_A by $q^{Apple} - \bar{q}_{t_A}^A$ so that the highest quality of this set of iPhones is adjusted to

[51] Fan and Yang (2019) develops an algorithm to simulate the equilibrium product set choices, but the algorithm is still computationally too complex to be embedded in dynamic game estimation.

q^{Apple}. Call this set of iPhones with adjusted qualities J_A. Note that this draw preserves the carrier affiliation in the data. I next draw a period t_H and adjust the qualities of HTC phones to obtain a set of HTC products J_H. To simulate the set for Samsung, I first discretize the observed η in data to three levels, $\{0.3, 0.5, 0.7\}$. η is the proportion of Samsung handsets using Qualcomm SoCs, defined as the number of Samsung phone-model-carrier pairs using Qualcomm divided by the total number of phone-model-carrier pairs by Samsung.[52] The variations of η in data are shown in Fig. 2. For the state s, I sample a period t_S from the set of periods where the observed proportion is equal to η^{Sam} and adjust the qualities of the Samsung smartphones. Denote the set of Samsung products as J_S. Note that this draw preserves both the carrier affiliation and the SoC usage of the Samsung products in t_S. I pair the joined set $J_A \cup J_H \cup J_S$ with the appropriate time fixed effects in t, a random vector of demand and marginal cost shocks and bargaining weights to calculate period profits for Qualcomm and downstream handset makers for this draw. Note that I do not need to additionally specify the carrier affiliation of the products in $J_A \cup J_H \cup J_S$ or the set of products using Qualcomm (J_Q): I maintain the carrier affiliation and SoC usage embedded in J_A, J_H and J_S.

C Solving, Estimating and Simulating the Dynamic Model

I set the quality increment for Qualcomm to be $\Delta = 0.25$, and $a^Q \in \{0, \mathit{\Delta}, 2\mathit{\Delta}, \ldots, 6\mathit{\Delta}\}$. 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's quality frontier directly, in addition to handset makers' quality frontiers and Samsung's proportion of handsets using Qualcomm SoCs. The value function is parameterized as a third degree complete polynomial of Apple, Samsung and HTC's quality levels. To precisely calculate the value function given δ^Q, η and t, I compute a different set of polynomial coefficients specific to each combination of $\left\{t, \eta, \delta^Q\right\}$, where $t = 1, \ldots, T$, $\eta \in \{30\%, 50\%, 70\%\}$, and $\delta^Q \in \{0, \delta, \ldots, 10\delta\}$. I solve the value functions at the zeros of the Chebyshev polynomials and

[52] Fan and Yang (2019) documents that on average, Samsung has 11 products per month, Apple 2.1 and HTC 10.4.

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

In the formulation of Shi and Shum (2015), data do not directly enter the inequality constraint. Instead, the inequality constraint (16) is converted into an equality constraint by introducing a slackness parameter and adding an inequality constraint that the slackness parameter is positive.

To construct the confidence set in (15), I use a genetic algorithm that searches through an 12-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 $g^{e\prime}Wg^e$ 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, 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's 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 SoCs, 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's quality when it is in generation S4. The first handset using the next generation Qualcomm SoC Snapdragon 600 is Galaxy S4. To construct the quality index for such a phone, I need to calibrate the SoC generation fixed effect. I choose 2.474 for the SoC effect, which is 0.8 larger than the S4 SoC generation effect in demand estimates. The incremental increase in the SoC effect in previous generations is less than 0.63. In choosing a large SoC fixed effect and hence a high upper bound for Qualcomm, I err on the side of understating the benefit of vertical integration.

I stratify points in the confidence set and sample points from each stratum to conduct counterfactual simulations. In principle, I can approximate the confidence set of the counterfactual predictions by using every point in the confidence set to simulate counterfactual scenarios, but this is computationally infeasible. The purpose of the stratified 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 longest 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. In Section 6, every sampled point is used to simulate each scenario 240 times. Increasing the number of strata to 6 and the number of sampled points to 24 do not significantly change the result.

D Additional Robustness Checks

I conduct two 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 monthly discount factor is set to be 0.5.

The 7 deviations to the assumptions in the main text are listed below. Robustness check 1 examines whether the results are sensitive to the modeling choice of the disagreement payoff in the bargaining model. Checks 2 and 3 examine whether the results are sensitive to the potential measurement errors in the markup data (Qualcomm chip division gross margins in its quarterly financial reports). Check 4 examines the sequential move assumption. Checks 5 and 6 examine whether the results are robust to the initial condition assumptions discussed in Appendix C. Check 7 examines the condition where the marginal cost of Qualcomm's SoC $\underline{\psi}$ and the price of the non-Qualcomm SoC, $\overline{\psi}$ increase over time. For the brevity of the presentation, I report the results from the vertical integration counterfactual. The subsidy counterfactual results are similar to the main specifications.

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 markup of Qualcomm's SoC. I use 0.9×observed margin to estimate the SoC pricing model.

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

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

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

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

7. $\underline{\psi}$ and $\overline{\psi}$ increase at a 0.4% monthly rate (5% annually).

Tables 16 through 22 report the counterfactual results. The results are mostly consistent with the main specification except for the third case. In this case, the increases in Qualcomm and Samsung's innovations are not significantly different from 0, but the innovation rate of HTC and the (unreported) welfare measures still are.

Finally, when the monthly discount factor is lowered to 0.5, I obtain the implausible result that Qualcomm innovation cost decreases in its innovation step size, conditional on innovation. The results are in Table 23. The exercise suggests that dynamic incentives are important in rationalizing the data.

Table 1: SoC 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

Table 2: SoC 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 SoCs and the adoption corresponds with the release of new Apple products.

Figure 1: Product Attribute Trends

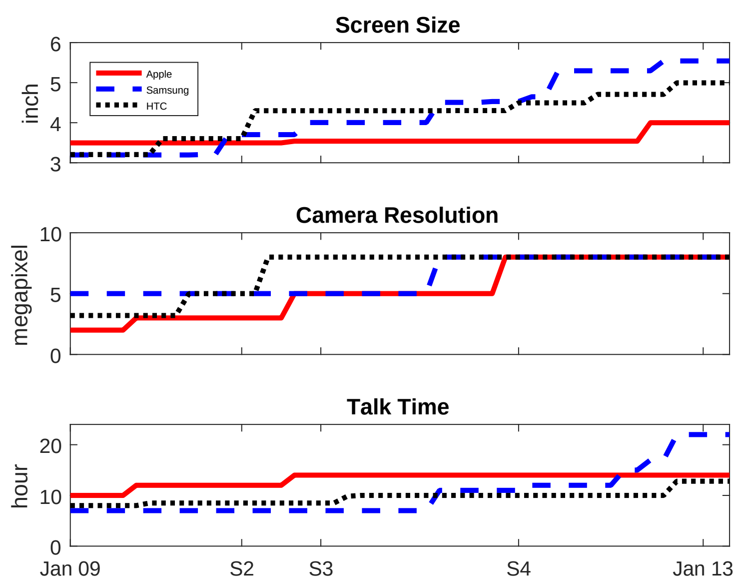
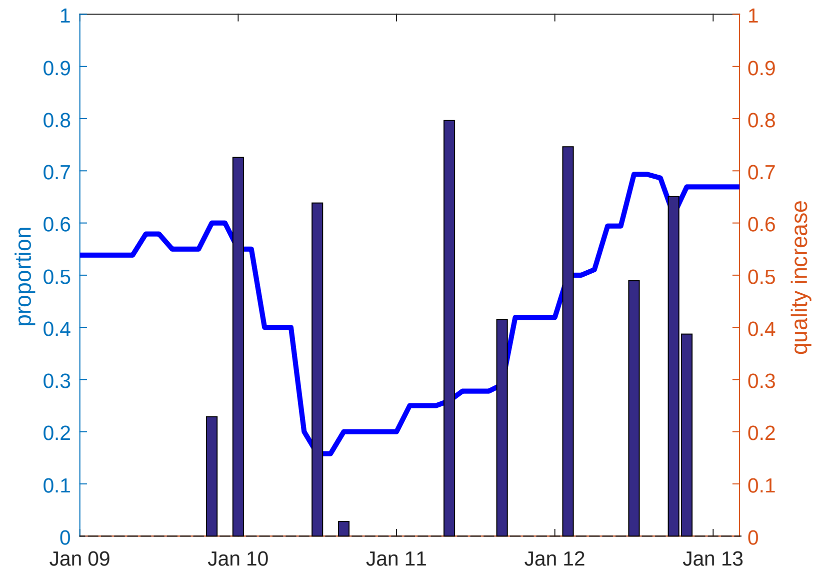


Figure 2: Samsung's Innovation and the Proportion of its Handsets Using Qualcomm SoCs



The line corresponds with the left axis, showing the proportion of Samsung handsets in that month that use Qualcomm SoCs. The proportion is defined as the number of Samsung products (e.g., Galaxy S3 on T-Mobile) using Qualcomm divided by the total number of Samsung products. The bars correspond with the right axis, showing the sizes of each Samsung's innovation. The size of the innovation is computed based on how much the quality index of each month's highest quality product increased from the previous month. The quality index is estimated based on the demand estimates in Section 5. From the graph, the proportions stayed roughly constant between two consecutive innovations.

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

Table 4: Demand Side Estimates

		Est	Se
β	Screen Size (inch)	1	-
	SoC Generation S1	0.460	0.113
	SoC Generation S2	0.718	0.147
	SoC Generation S3	1.055	0.200
	SoC 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	SoC prices ($)	[28.71, 51.29]	35.91

Values inverted from the bargaining FOCs (12)

τ: across 17 quarters; ψ_t: all Qualcomm-powered products, 51 months.

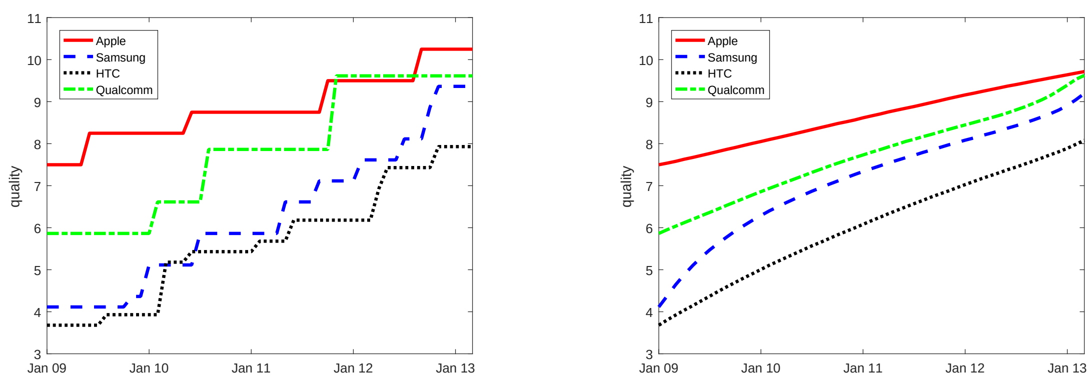
Table 6: Estimates of Innovation Costs

		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 (15) and is not a Cartesian product of the intervals above.

Figure 3: Quality Frontier Evolution

Data | Simulation



I plot the brand-fixed effect adjusted quality frontiers $q_t^n + \frac{\theta_n}{\bar{\beta}_0}$ for handset makers in data and simulation. The Qualcomm line on the left represents the upper bound of Qualcomm's quality in data. The Qualcomm line on the right represents the simulated quality of Qualcomm. The lower bound is the upper envelope of Samsung and HTC qualities. The simulated quality frontier is the average of 960 simulated paths based on a random draw of parameters in the confidence set. The vertical axis is in the unit of quality indices constructed from the demand estimates. Qualcomm's quality is adjusted with Samsung brand fixed effects.

Table 7: Confidence Intervals of the Expected Total Investment ($ 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]

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

		(1)	(2)	(3)	(4)
Innovation Rate: $(q_{36} - q_1)/35$	Apple	[0.0403, 0.0444]	[0.0403, 0.0444]	[0.0414, 0.0456]	[0.0414, 0.0454]
	Samsung	[0.1073, 0.1176]	[0.1073, 0.1176]	[0.1282, 0.1305]	[0.1294, 0.1318]
	HTC	[0.0783, 0.0828]	[0.0783, 0.0828]	[0.0933, 0.0951]	[0.0939, 0.0955]
	Qualcomm	[0.0731, 0.0863]	[0.0731, 0.0863]	[0.0972, 0.0986]	[0.0979, 0.0999]
SoC Price ($)	Samsung	[31.36, 31.37]	[32.30, 32.35]	[31.41, 31.41]	[32.49, 32.52]
	HTC	[31.39, 31.40]	[16.70, 16.70]	-	[16.70, 16.70]
Retail Price ($)	Apple	[160.25, 164.04]	[160.17, 163.96]	[160.02, 164.23]	[159.86, 163.92]
	Samsung	[224.96, 231.30]	[225.13, 231.50]	[239.60, 245.45]	[241.42, 247.19]
	HTC	[198.16, 202.45]	[184.47, 188.83]	[212.16, 213.78]	[199.47, 200.75]
Proportion of Samsung Handsets Using Qualcomm		[0.45, 0.49]	[0.45, 0.49]	[0.57, 0.59]	[0.57, 0.59]
Consumer Surplus ($ Billion)		[22.81, 23.51]	[23.03, 23.73]	[24.32, 24.66]	[24.64, 24.94]
Producer Surplus ($ Billion)	Apple	[16.26, 16.71]	[16.24, 16.69]	[16.03, 16.56]	[15.99, 16.50]
	Samsung	[5.30, 5.56]	[5.28, 5.54]	[5.79, 6.10]	[5.83, 6.13]
	HTC+Qualcomm	[2.83, 2.99]	[2.85, 3.01]	[3.34, 3.42]	[3.39, 3.46]
CS+PS ($ Billion)		[47.31, 48.55]	[47.50, 48.74]	[49.87, 50.59]	[50.22, 50.85]
Investment ($ Billion)	Apple	[5.00, 5.75]	[5.00, 5.75]	[5.48, 6.17]	[5.44, 6.17]
	Samsung	[1.99, 2.51]	[1.99, 2.51]	[2.36, 2.86]	[2.38, 2.89]
	HTC	[2.82, 3.39]	[2.82, 3.39]	[5.02, 5.19]	[5.13, 5.24]
	Qualcomm	[0.56, 0.65]	[0.56, 0.65]	[0.87, 0.92]	[0.88, 0.94]

Table 10: 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]

Table 9: Counterfactual Results: Integrated Qualcomm Loses Patent Licensing Revenues, Jan 2009 to Dec 2011

		(1)	(2)	(3)	(4)
Innovation Rate: $(q_{36} - q_1)/35$	Apple	[0.0359, 0.0420]	[0.0359, 0.0420]	[0.0370, 0.0434]	[0.0380, 0.0443]
	Samsung	[0.0975, 0.1159]	[0.0975, 0.1159]	[0.1155, 0.1384]	[0.1013, 0.1140]
	HTC	[0.0712, 0.0910]	[0.0712, 0.0910]	[0.0909, 0.1064]	[0.0819, 0.0960]
	Qualcomm	[0.0597, 0.0792]	[0.0597, 0.0792]	[0.0789, 0.1034]	[0.0641, 0.0775]
SoC Price ($)	Samsung	[28.69, 28.77]	[29.85, 30.18]	[30.15, 30.43]	[32.37, 32.56]
	HTC	[25.24, 25.27]	[16.70, 16.70]	-	[16.70, 16.70]
Retail Price ($)	Apple	[157.46, 163.61]	[157.13, 163.22]	[157.15, 163.83]	[157.79, 164.12]
	Samsung	[216.30, 236.84]	[216.41, 236.88]	[234.29, 260.37]	[223.74, 237.01]
	HTC	[192.09, 217.51]	[157.48, 183.15]	[177.61, 197.54]	[190.56, 208.66]
Proportion of Samsung Handsets Using Qualcomm		[0.46, 0.49]	[0.46, 0.49]	[0.50, 0.53]	[0.46, 0.48]
Consumer Surplus ($ Billion)		[22.19, 24.15]	[22.84, 24.89]	[24.47, 26.82]	[22.65, 24.31]
Producer Surplus ($ Billion)	Apple	[15.47, 16.18]	[15.36, 16.06]	[15.17, 15.94]	[15.95, 16.71]
	Samsung	[5.13, 6.05]	[5.07, 5.98]	[5.78, 6.96]	[5.10, 5.70]
	HTC+Qualcomm	[9.15, 10.46]	[9.43, 10.79]	[10.60, 11.79]	[3.08, 3.69]
CS+PS ($ Billion)		[52.15, 56.19]	[52.92, 57.04]	[56.12, 60.70]	[46.87, 49.85]
Investment ($ Billion)	Apple	[4.12, 4.39]	[4.12, 4.39]	[4.48, 5.04]	[4.61, 5.43]
	Samsung	[0.43, 0.63]	[0.43, 0.63]	[0.56, 0.76]	[0.43, 0.61]
	HTC	[1.89, 2.99]	[1.89, 2.99]	[4.40, 5.03]	[3.20, 3.98]
	Qualcomm	[1.11, 2.12]	[1.11, 2.12]	[2.41, 3.43]	[1.36, 2.11]

Table 11: Counterfactual Results: Fixed Qualcomm's Quality Path, Jan 2009 to Dec 2011

		(1)	(2)	(3)	(4)
	Apple	[0.0491, 0.0548]	[0.0491, 0.0548]	[0.0485, 0.0540]	[0.0485, 0.0539]
Innovation Rate:	Samsung	[0.0853, 0.0892]	[0.0853, 0.0892]	[0.0876, 0.0884]	[0.0878, 0.0885]
$(q_{36} - q_1)/35$	HTC	[0.0707, 0.0774]	[0.0707, 0.0774]	[0.0753, 0.0776]	[0.0754, 0.0777]
SoC Price ($)	Samsung	[31.33, 31.35]	[32.13, 32.27]	[31.35, 31.35]	[32.21, 32.26]
	HTC	[31.37, 31.39]	[16.70, 16.70]	-	[16.70, 16.70]
	Apple	[172.68, 179.66]	[172.57, 179.53]	[171.68, 177.96]	[171.47, 177.79]
Retail Price ($)	Samsung	[182.44, 208.64]	[182.63, 208.85]	[195.67, 199.86]	[196.68, 200.60]
	HTC	[188.58, 198.89]	[174.73, 185.16]	[195.22, 198.93]	[181.59, 185.27]
Proportion of Samsung Handsets Using Qualcomm		[0.42, 0.45]	[0.42, 0.45]	[0.50, 0.51]	[0.50, 0.51]
Consumer Surplus ($ Billion)		[21.73, 22.91]	[21.94, 23.12]	[22.29, 23.03]	[22.55, 23.29]
	Apple	[17.96, 18.97]	[17.93, 18.94]	[17.88, 18.68]	[17.83, 18.63]
Producer Surplus	Samsung	[3.38, 4.40]	[3.37, 4.39]	[3.87, 4.01]	[3.89, 4.02]
($ Billion)	HTC+Qualcomm	[2.44, 2.81]	[2.45, 2.83]	[2.67, 2.80]	[2.69, 2.82]
CS+PS ($ Billion)		[45.80, 48.06]	[45.99, 48.26]	[46.84, 48.35]	[47.09, 48.61]
	Apple	[6.45, 7.83]	[6.45, 7.83]	[6.46, 7.35]	[6.43, 7.34]
Investment	Samsung	[0.50, 1.19]	[0.50, 1.19]	[0.49, 0.56]	[0.49, 0.55]
($ Billion)	HTC	[1.85, 2.58]	[1.85, 2.58]	[2.31, 2.68]	[2.34, 2.70]

Table 12: Counterfactual Results, Jan 2009 to Mar 2013

		(1)	(2)	(3)	(4)
	Apple	[0.0371, 0.0445]	[0.0430, 0.0437]	[0.0386, 0.0454]	[0.0385, 0.0453]
Innovation Rate:	Samsung	[0.0882, 0.1095]	[0.0990, 0.1007]	[0.1130, 0.1240]	[0.1138, 0.1247]
$(q_{36} - q_1)/35$	HTC	[0.0724, 0.0876]	[0.0804, 0.0831]	[0.0855, 0.1008]	[0.0861, 0.1011]
	Qualcomm	[0.0621, 0.0856]	[0.0736, 0.0753]	[0.0867, 0.0982]	[0.0877, 0.0989]
SoC Price ($)	Samsung	[29.24, 29.28]	[30.37, 30.42]	[29.30, 29.33]	[30.49, 30.70]
	HTC	[29.29, 29.32]	[15.57, 15.57]	-	[15.57, 15.57]
	Apple	[122.46, 131.07]	[129.22, 130.25]	[123.71, 131.56]	[123.31, 131.22]
Retail Price ($)	Samsung	[193.67, 219.96]	[208.68, 211.65]	[229.30, 245.69]	[231.44, 247.53]
	HTC	[167.79, 186.46]	[164.60, 168.62]	[182.16, 203.42]	[170.47, 191.60]
Proportion of Samsung Handsets Using Qualcomm		[0.39, 0.46]	[0.43, 0.43]	[0.48, 0.58]	[0.48, 0.57]
Consumer Surplus ($ Billion)		[28.47, 32.40]	[31.36, 31.69]	[31.74, 34.98]	[32.19, 35.46]
	Apple	[19.37, 20.45]	[20.12, 20.32]	[19.23, 20.31]	[19.13, 20.22]
Producer Surplus	Samsung	[7.01, 8.29]	[7.68, 7.85]	[8.79, 9.51]	[8.85, 9.52]
($ Billion)	HTC+Qualcomm	[4.07, 4.83]	[4.46, 4.64]	[4.71, 5.62]	[4.78, 5.69]
CS+PS ($ Billion)		[58.91, 65.78]	[63.82, 64.32]	[64.47, 70.01]	[64.95, 70.48]
	Apple	[6.59, 7.59]	[6.77, 7.02]	[7.12, 7.99]	[7.04, 7.93]
Investment	Samsung	[1.80, 3.24]	[2.53, 2.63]	[2.18, 3.60]	[2.20, 3.63]
($ Billion)	HTC	[3.01, 4.66]	[3.62, 4.06]	[4.95, 6.85]	[5.08, 6.95]
	Qualcomm	[0.60, 0.84]	[0.71, 0.74]	[0.96, 1.20]	[0.97, 1.21]

Figure 4: Qualcomm Paths

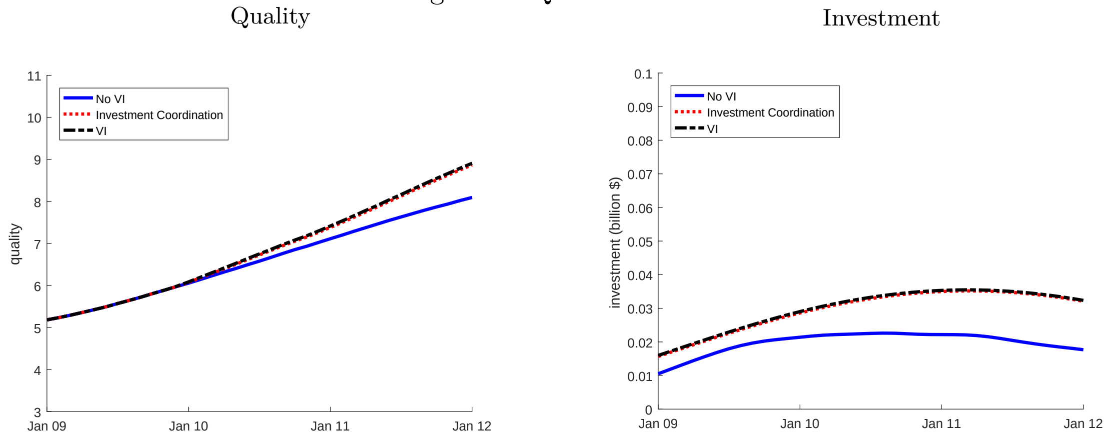


Figure 5: Apple Paths

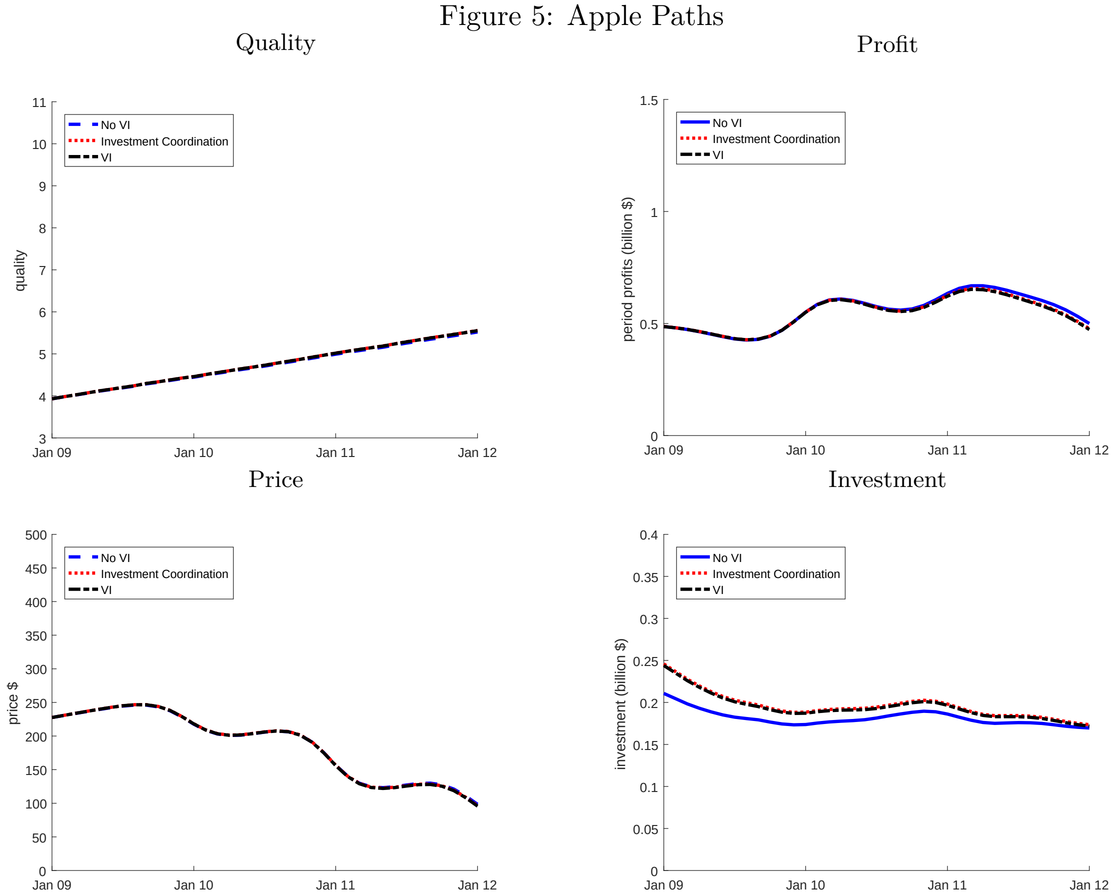


Figure 6: Samsung Paths

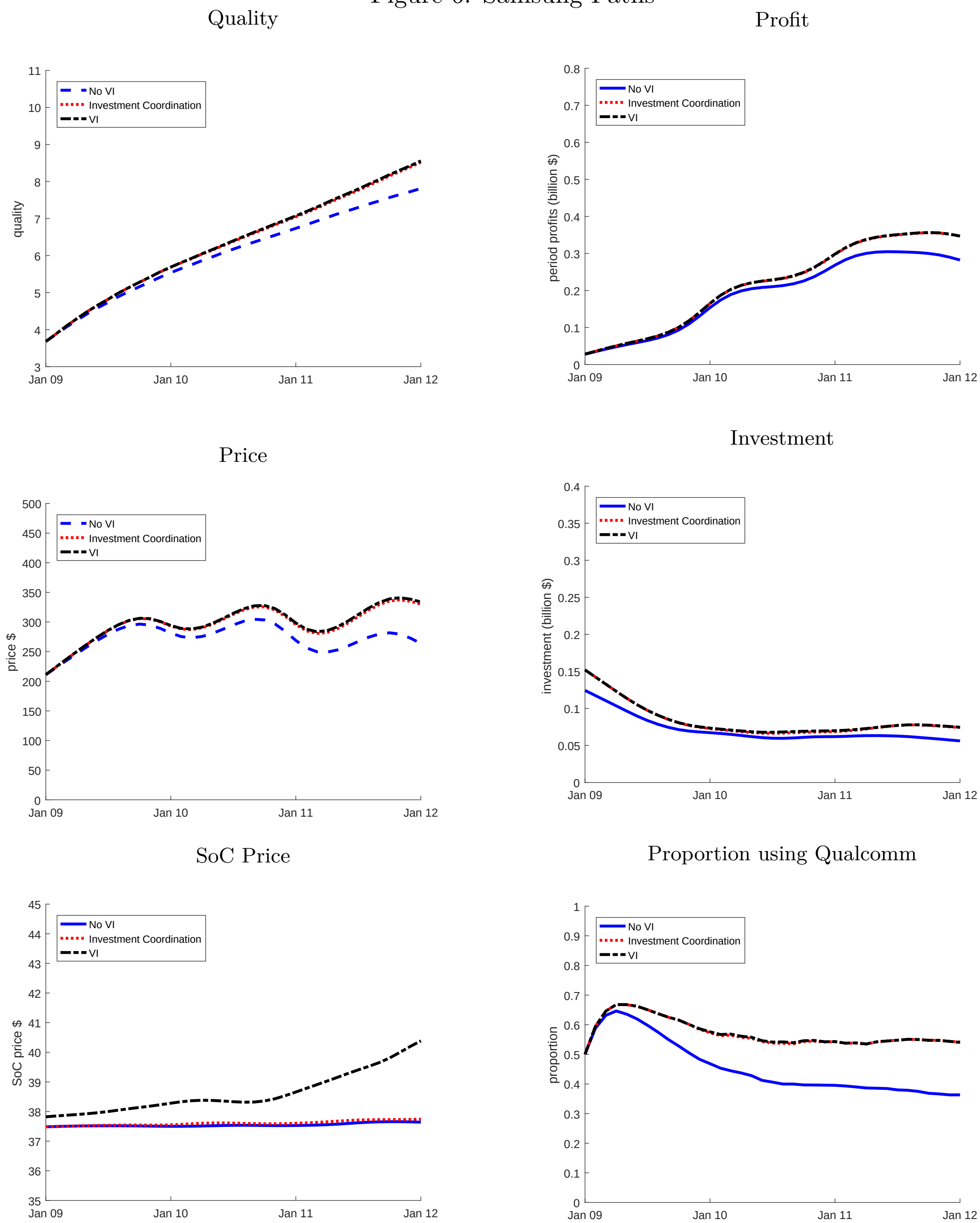


Figure 7: HTC Paths

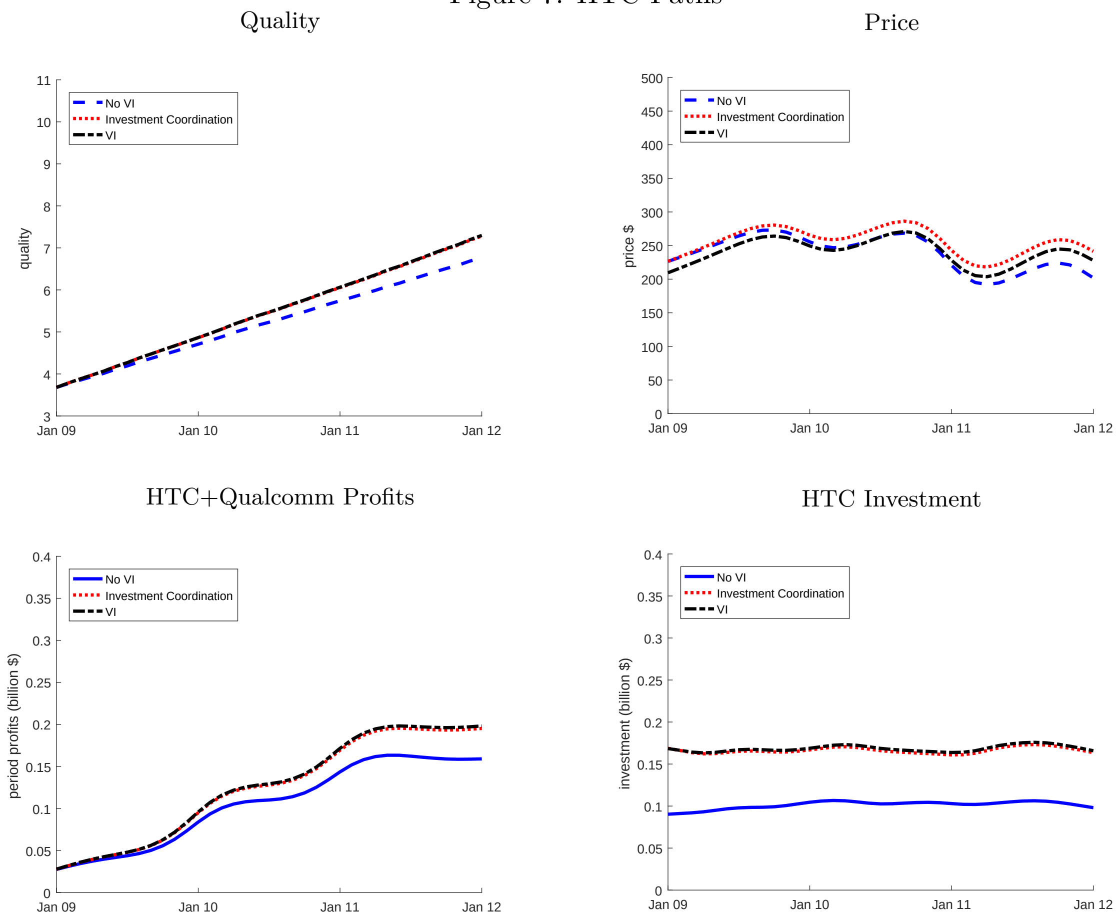


Figure 8: Welfare Paths

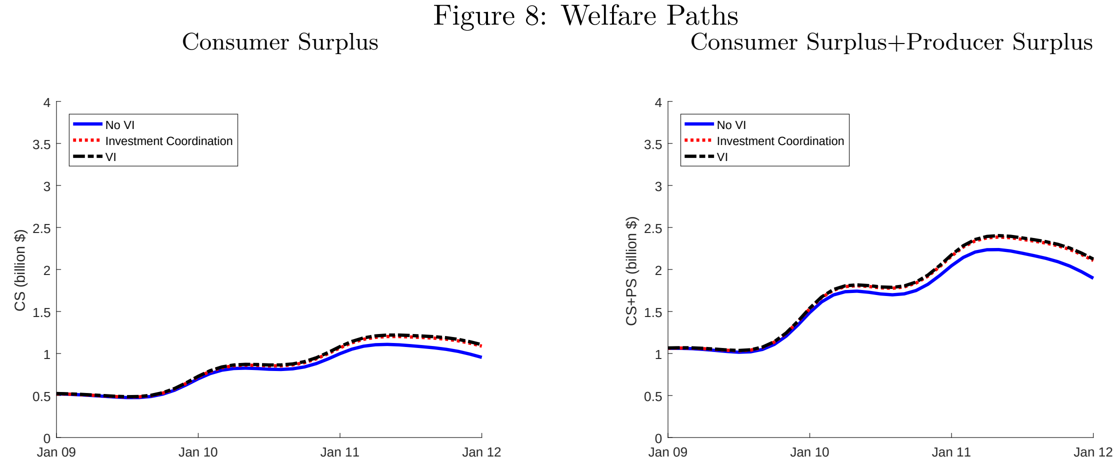


Table 13: Counterfactual Results: Licensing Revenues, Jan 2009 to Dec 2011

		No VI	Full VI
Innovation Rate:	Apple	[0.0359, 0.0420]	[0.0370, 0.0434]
$(q_{36} - q_1)/35$	Samsung	[0.0975, 0.1159]	[0.1155, 0.1384]
	HTC	[0.0712, 0.0910]	[0.0909, 0.1064]
	Qualcomm	[0.0597, 0.0792]	[0.0789, 0.1034]
Consumer Surplus ($ Billion)		[22.19, 24.15]	[24.47, 26.82]
CS+PS ($ Billion)		[52.15, 56.19]	[56.12, 60.70]

Figure 9: The Effects of Qualcomm Subsidies

Change of Innovation Rates — Subsidy, and Change of Surpluses and Investment

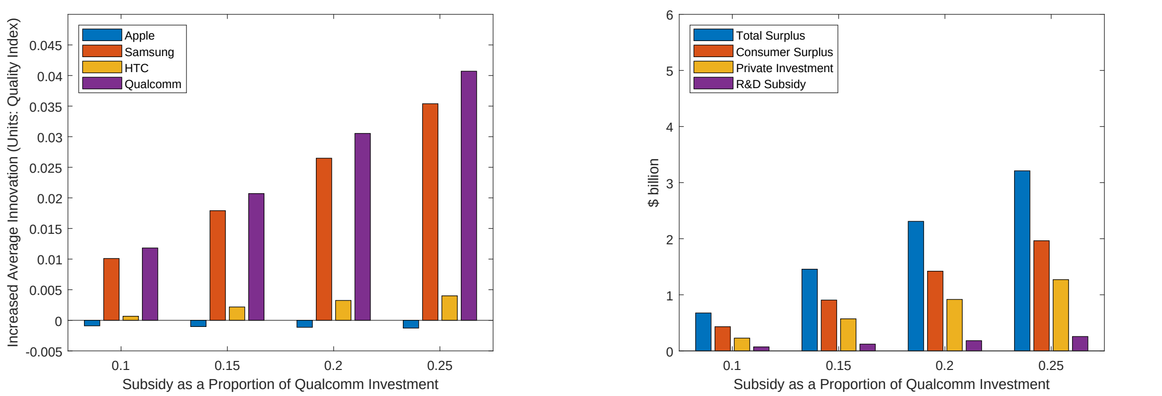


Figure 10: The Effects of Qualcomm Subsidies, All 51 Periods

Change of Innovation Rates — Subsidy, and Change of Surpluses and Investment

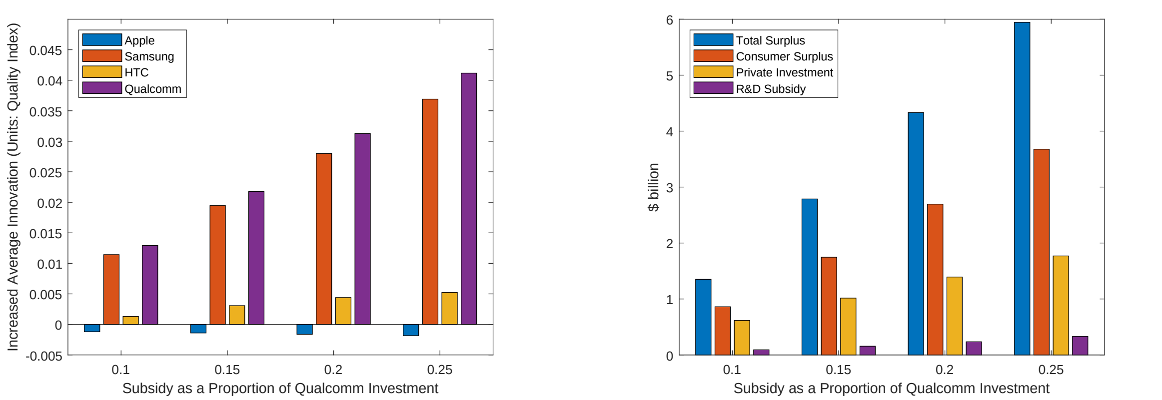


Figure 11: The Effects of VI and a 15% Subsidy to Qualcomm At Different Horizon Lengths

Change of Innovation Rates Due to VI

Change of Innovation Rates Due to 15% Qualcomm Innovation Cost Subsidy

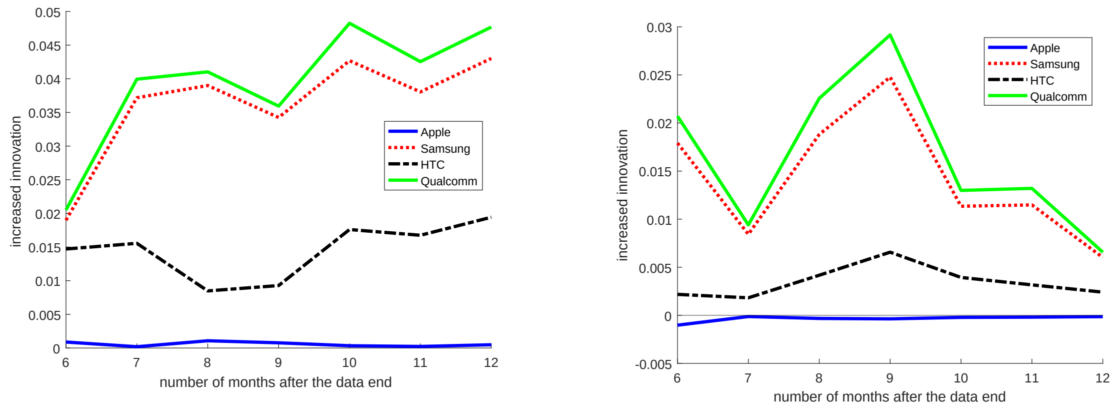


Table 14: Counterfactual Results, Ending the Game 12 Months after the Data

		No VI	Full VI
	Apple	[0.0394, 0.0495]	[0.0399, 0.0501]
Innovation Rate:	Samsung	[0.0928, 0.1091]	[0.1297, 0.1594]
$(q_{36} - q_1)/35$	HTC	[0.0647, 0.0940]	[0.0865, 0.1195]
	Qualcomm	[0.0569, 0.0737]	[0.0994, 0.1277]
Consumer Surplus ($ Billion)		[21.72, 23.90]	[25.31, 28.11]
CS+PS ($ Billion)		[47.48, 51.69]	[53.51, 58.00]

Figure 12: The Effects of Qualcomm Subsidies, Ending the Game 12 Months after the Data

Change of Innovation Rates

Subsidy, and Change of Surpluses and Investment

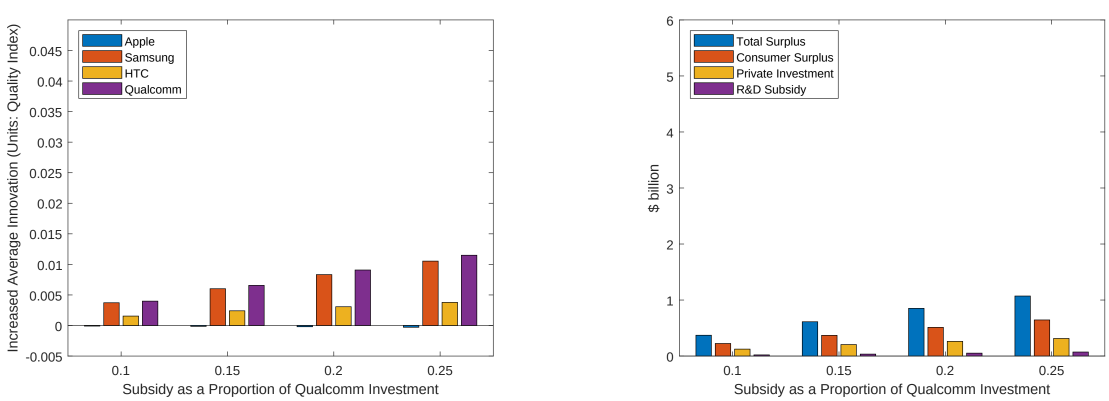


Figure 13: Total Monthly Mobile Phone Unit Sales and Smartphone Unit Sales, 09-13Q1, US

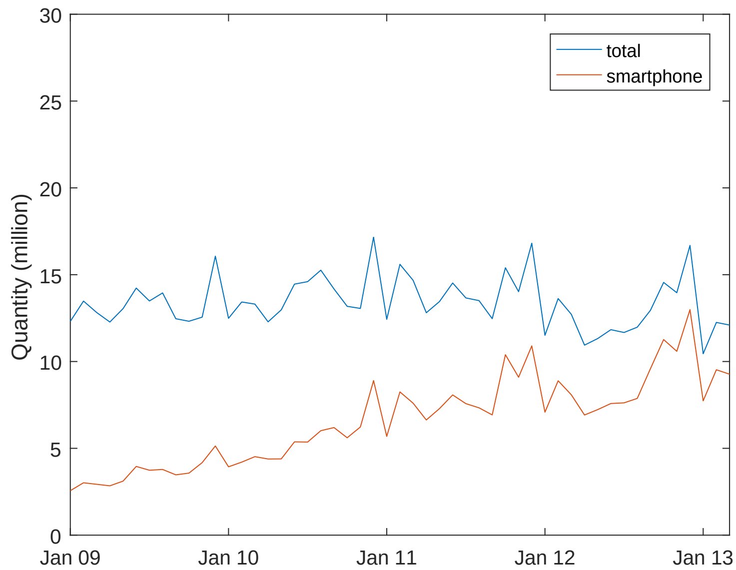


Table 15: Counterfactual Results, Alternative Market Size Definition

		No VI	Full VI
Innovation Rate: $(q_{36} - q_1)/35$	Apple	[0.0321, 0.0367]	[0.0326, 0.0365]
	Samsung	[0.0898, 0.0904]	[0.1357, 0.1368]
	HTC	[0.0817, 0.0827]	[0.0954, 0.0967]
	Qualcomm	[0.0539, 0.0547]	[0.1071, 0.1081]
Consumer Surplus ($ Billion)		[23.38, 23.87]	[27.03, 27.51]
CS+PS ($ Billion)		[48.32, 49.39]	[54.17, 55.12]

Figure 14: The Effects of Qualcomm Subsidies, Alternative Market Size Definition

Change of Innovation Rates

Subsidy, and Change of Surpluses and Investment

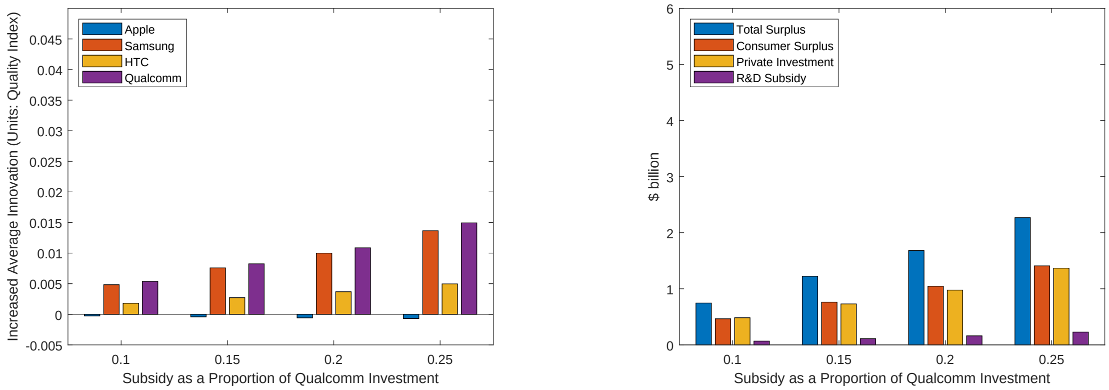


Table 16: Counterfactual Results, Robustness Check 1

		No VI	Full VI
Innovation Rate:	Apple	[0.0417, 0.0422]	[0.0429, 0.0432]
$(q_{36} - q_1)/35$	Samsung	[0.1023, 0.1198]	[0.1146, 0.1221]
	HTC	[0.0831, 0.0884]	[0.0950, 0.0960]
	Qualcomm	[0.0666, 0.0863]	[0.0803, 0.0885]

Table 17: Counterfactual Results, Robustness Check 2

		No VI	Full VI
Innovation Rate:	Apple	[0.0406, 0.0427]	[0.0416, 0.0436]
$(q_{36} - q_1)/35$	Samsung	[0.1037, 0.1125]	[0.1458, 0.1488]
	HTC	[0.0833, 0.0888]	[0.0976, 0.0986]
	Qualcomm	[0.0681, 0.0779]	[0.1143, 0.1186]

Table 22: Counterfactual Results: Robustness Check 7

		No VI	Full VI
Innovation Rate:	Apple	[0.0434, 0.0454]	[0.0446, 0.0464]
$(q_{36} - q_1)/35$	Samsung	[0.1051, 0.1205]	[0.1380, 0.1511]
	HTC	[0.0745, 0.0886]	[0.0914, 0.1038]
	Qualcomm	[0.0704, 0.0877]	[0.1042, 0.1198]

Table 18: Counterfactual Results, Robustness Check 3

		No VI	Full VI
Innovation Rate:	Apple	[0.0371, 0.0464]	[0.0385, 0.0472]
$(q_{36} - q_1)/35$	Samsung	[0.1042, 0.1153]	[0.1070, 0.1085]
	HTC	[0.0834, 0.0889]	[0.0939, 0.0951]
	Qualcomm	[0.0692, 0.0838]	[0.0737, 0.0749]

Table 19: Counterfactual Results, Robustness Check 4

		No VI	Full VI
Innovation Rate:	Apple	[0.0405, 0.0407]	[0.0410, 0.0411]
$(q_{36} - q_1)/35$	Samsung	[0.1030, 0.1070]	[0.1155, 0.1180]
	HTC	[0.0745, 0.0854]	[0.0909, 0.0969]
	Qualcomm	[0.0677, 0.0736]	[0.0831, 0.0859]

Table 20: Counterfactual Results, Robustness Check 5

		No VI	Full VI
Innovation Rate:	Apple	[0.0380, 0.0443]	[0.0385, 0.0442]
$(q_{36} - q_1)/35$	Samsung	[0.0877, 0.1054]	[0.1359, 0.1441]
	HTC	[0.0771, 0.0971]	[0.1068, 0.1309]
	Qualcomm	[0.0752, 0.0910]	[0.1308, 0.1367]

Table 21: Counterfactual Results, Robustness Check 6

		No VI	Full VI
Innovation Rate:	Apple	[0.0401, 0.0477]	[0.0404, 0.0475]
$(q_{36} - q_1)/35$	Samsung	[0.0895, 0.1054]	[0.1198, 0.1481]
	HTC	[0.0566, 0.0778]	[0.0667, 0.1066]
	Qualcomm	[0.0906, 0.1067]	[0.1209, 0.1518]

Table 23: Estimates of Innovation Costs At A Lower Discount Rate

		$\delta = 0.5$
γ_0	Apple	[-0.67, 0.98]
	Samsung	[-0.43, -0.18]
	HTC	[-0.38, -0.01]
	Qualcomm	[-2.89, -2.89]
γ_1	Apple	[29.92, 34.11]
	Samsung	[15.07, 15.07]
	HTC	[14.44, 15.32]
	Qualcomm	[-5.65, -5.03]
γ_2	Samsung	[2.95, 3.52]
σ	Handset	[10.80, 10.80]
	Qualcomm	[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 (15) and is not a Cartesian product of the intervals above.

Table 24: Parameter Perturbation

		Change in Own Innovation Rates
γ_0	Apple	-0.0004
	Samsung	-0.0002
	HTC	-0.0002
	Qualcomm	-0.0356
γ_1	Apple	-0.0035
	Samsung	-0.002
	HTC	-0.0069
	Qualcomm	-0.0115
γ_2	Samsung	0.0013

I report changes in own innovation rates, comparing the innovation rates at the parameters that are mid points of the intervals in Table 6 and the innovation rates if one parameter is increased by 10% of its absolute value. One parameter is perturbed at a time, and thus the table reflects the changes of innovation rates from 9 sets of simulations, 240 paths per set.