The Welfare Effects of Government Intervention into the Licensing of Standard-Essential Patents

An Analysis of the Chinese Smartphone and SoC Markets

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Abstract

The licensing of standard-essential patents ("SEPs") in the cellular communications field has been a contentious issue. In particular, the licensing policies of Qualcomm for third-generation and fourth-generation cellular communication standards have been the subject of several lawsuits and government intervention episodes. Given Qualcomm's dual role as a technology licensor as well as a supplier of baseband processors and System-on-Chips ("SoCs") to smartphone manufacturers, there has been a concern that Qualcomm's royalties on smartphone sales could have an exclusionary effect on rival chipmakers and cause consumers to pay higher prices for smartphones. We evaluate the impact of the most drastic intervention to date: the Chinese government's 2015 decision to forcibly lower Qualcomm royalty rates by 1.23 - 1.75 percentage points. Using a simple theoretical model, we argue that such an intervention could have ambiguous effects on consumers; it could lead to higher or lower smartphone prices. To quantify the policy's impact, we construct a structural econometric model of the Chinese smartphone and SoC markets which allows for strategic pricing in the two vertically related markets. Counterfactual analysis using the estimated model allows us to quantify the intervention's impact on smartphone manufacturers' marginal costs and product prices. Our simulation results indicate that the intervention tended to cause an increase in smartphone manufacturers' marginal costs (around 1.1 percent on average). However, this was more than offset by smartphone manufacturers' incentive to lower their prices under the reduced royalty rate, leading to a slight reduction in smartphone prices (around 0.6 percent on average). Taken together, these results suggest that the Chinese government's intervention had the intended effect on social welfare, although its magnitude was fairly limited.

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1 Introduction

Technology standards have played an important role in the development of high-tech industries in which key innovations are realized by multiple entities. By coalescing around a specific standard, different firms can develop products and services that are compatible with each other, generating significant benefits to consumers. However, when multiple entities contribute to the development of a single standard, the issue of how to compensate each innovator arises. To avoid potential problems of hold-up and "royalty stacking" – the phenomenon where each patent holder sets its profit-maximal royalty rate and the summed royalty rate becomes prohibitively high – standard-setting organizations have required contributing innovators to commit to licensing their standard-essential patents ("SEPs") on a fair, reasonable, and non-discriminatory ("FRAND") basis.

In the area of cellular communication, the actual meaning of FRAND has often been the subject of legal dispute between SEP holders and the implementers of patented technology. One of the most high-profile of these disputes, playing out in multiple jurisdictions over many years, involves Qualcomm and its SEPs for cellular communication standards. Qualcomm has held a unique position in this industry, as both the largest owner of SEPs and a leading supplier of microchips that enable cellular handsets (smartphones and feature phones) to connect to cellular networks.[1] These microchips include both standalone modem chips (called "baseband processors") and System-on-Chips ("SoCs"), which are integrated circuits that combine a modem with various other functions.[2]

Qualcomm's opponents have accused the firm of charging supra-FRAND royalties for its SEPs by (i) refusing to license its SEPs to other chipmakers, instead collecting royalties from handset manufacturers regardless of whether or not they use Qualcomm-made chips; and (ii) employing a coercive "no chips, no license" policy which made it difficult for handset manufacturers to dispute Qualcomm's licensing terms. According to the Federal Trade Commission ("FTC"), which sued Qualcomm in 2017, Qualcomm's elevated royalty rates caused handset prices to increase, thereby causing harm to consumers.[3]

This paper is motivated by the question of whether Qualcomm's licensing practices actually harmed consumers through higher handset prices. As we show using a simple vertical oligopoly model where a supplier of an intermediate product charges a royalty to manufacturers of the final product, raising the royalty rate can either increase or decrease the final product price. This is because the increase in royalty rate has two competing effects: (i) it reduces the marginal revenue of final product manufacturers, incentivizing them to reduce supply by raising their prices; and (ii) it enables the supplier-licensor and its competitors to lower the price of the component, which tends to lower the final product price.

We explore this research question in the context of the Chinese smartphone and SoC markets. Our choice of China as the setting has two motivations. First, the Chinese government's National Development and Reform Commission ("NDRC") found in 2015 that Qualcomm's licensing practices violated the country's Anti-Monopoly Law. The NDRC alleged that Qualcomm's royalty rates were

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[1] Throughout this paper, we use the terms "handsets" and "smartphones" interchangeably. Although some of the handsets appearing in our dataset are feature phones, a large majority of the handsets are smartphones, especially in the more recent years.

[2] For the most part, we refer to these microchips collectively as SoCs or simply "chips", but clarify the distinction between SoCs and baseband processors whenever necessary.

[3] See FTC's complaint in Federal Trade Commission v. Qualcomm Inc. (N.D. Cal. 2019), available at `https://www.ftc.gov/legal-library/browse/cases-proceedings/141-0199-qualcomm-inc`

unfairly high, causing rival chipmakers to lose competitiveness and raising the costs faced by handset manufacturers. This, in turn, caused an increase in handset prices and harmed consumers, according to the NDRC.[4] Upon the NDRC's orders, Qualcomm had to lower the royalty rates charged to smartphone manufacturers in China. While other competition agencies such as the FTC and the Korean Fair Trade Commission have made similar allegations, at the time of writing, the NDRC is alone in having forced a reduction in Qualcomm's royalty rates. Thus, the NDRC intervention presents a valuable case study for examining whether drastic government intervention, in the form of a forcible reduction of royalty rates, is justified on consumer welfare grounds.

The second motivation is the relatively competitive nature of the Chinese SoC market, which allows an exogenous change in Qualcomm's royalty rates, such as that imposed by the NDRC, to have a palpable effect on competition. In particular, one of Qualcomm's rival chipmakers – which we shall call M – is a major supplier to many Chinese smartphone manufacturers, all of whom pay royalties to Qualcomm.[5,6] If, as the NDRC and other competition agencies claim, Qualcomm's excessive royalties had an exclusionary effect on rival chipmakers such as M, the NDRC intervention may have reversed it to some extent, causing rival chipmakers' profits to increase. We aim to quantify this profit increase and thereby evaluate the intervention's role in alleviating exclusionary effects.

To pursue these aims, we construct a structural econometric model of the Chinese smartphone and SoC markets. The demand for smartphones is modeled using a two-level nested logit framework and estimated from product-level market share data for individual cities. Smartphone manufacturers, all of whom are multi-product firms, are assumed to maximize profit by choosing their product prices. The prices of SoCs – whose identities are recorded for each smartphone model in our data – are taken as given by the smartphone manufacturers. SoC suppliers, who are also multi-product firms, are assumed to maximize profit by choosing their product prices, taking the derived demand from smartphone manufacturers as given. To estimate the marginal costs of smartphone manufacturers, we use the first-order conditions for profit maximization in the smartphone market. These marginal costs include the cost of SoC procurement; we are unable to separate out the SoC cost from non-SoC costs because we do not have data on SoC prices. In our analysis of the SoC market, we therefore derive the price-cost margins of SoC manufacturers, rather than their marginal costs, using the first-order conditions for profit maximization.

We evaluate the impact of the NDRC intervention in 2015 by conducting counterfactual simulations for each market. Our counterfactual scenario consists of Qualcomm maintaining the same royalty rates that it had in place in 2014 beyond 2015, instead of the reduced rates imposed by the intervention. We use the estimated structural model to compute equilibrium price-cost margins in the SoC market as well as prices in the smartphone market under the counterfactual scenario. By comparing outcomes under the counterfactual scenario against the actual outcomes, we are able to quantify the effect of the NDRC intervention. Our results show that SoC manufacturers' price-cost

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[4] See National Development and Reform Commission Administrative Sanction Decision No. 1 [2015], dated February 9, 2015; available from IPR Daily at `http://www.iprdaily.cn/article_6967.html`.

[5] Under the terms of our agreement with GfK, our data provider, we are unable to disclose the full names of the companies that appear in our dataset with the exception of Qualcomm.

[6] In contrast to China, other countries tend to have SoC markets that are dominated by Qualcomm. For example, Yang (2020) notes that in the U.S., most of Qualcomm's rivals in the SoC market have exited by 2012 and the remaining substantial rival, Samsung, is a vertically integrated firm whose smartphone division procures almost half of its SoC requirements from Qualcomm.

margins – and by extension, SoC prices – were unequivocally increased by the NDRC intervention, conforming with predictions from our theoretical model. The effect of the intervention on smartphone prices varies across models in terms of sign, which also conforms with theoretical predictions. However, we find that the quantity-weighted average price of smartphones decreased in response to the intervention in every analyzed market. This translates into a small but significant increase in consumer surplus.

Relationship to Literature. The behavior of firms that act as both component supplier and patent licensor has been analyzed theoretically by Padilla and Wong-Ervin (2017), Kim (2020) and Shapiro and Waehrer (2023). The first two papers focus on the supplier-licensor's decision with regard to royalty base – whether to license to rival component suppliers or final good manufacturers – and royalty rate. Padilla and Wong-Ervin (2017) find that a supplier-licensor's refusal to license component suppliers (i.e., licensing only to final product manufacturers) cannot be anticompetitive in a specific class of vertical oligopoly models.[7] Kim (2020) examines the supplier-licensor's incentive to foreclose rival component suppliers by either suing them for patent infringement or raising the royalty rate. He finds that the likelihood of foreclosure varies with both the royalty base (either components or final products) and the structure of demand and supply.

In contrast to these papers, we do not focus on the supplier-licensor's choice of royalty base or royalty rate. Rather, we take as given that the royalty is assessed on the final product, and assume that its rate is exogenously determined. The exogeneity assumption is motivated by the fact that Qualcomm and other SEP holders are bound by FRAND commitments.[8] Our focus is instead on how changes in the royalty rate affect the prices of components and final products through the competitive interactions among firms. In this sense, our motivation is similar to that of Shapiro and Waehrer (2023) who specifically examine the FTC's allegations against Qualcomm by the FTC. After arguing that Qualcomm's licensing practices led to higher royalty rates, they examine whether the higher royalty rates had anticompetitive effects. Using a simplified model that focuses on the upstream chip market, Shapiro and Waehrer (2023) argue that Qualcomm's elevated royalty rate caused handset manufacturers to pay higher "all-in prices" for chips (inclusive of royalty payments to Qualcomm). This, they claim, led to higher handset prices paid by consumers. Our theoretical analysis in section 2 examines the impact of an elevated royalty rate on upstream and downstream prices using a vertical oligopoly model. We find that the equilibrium price of the intermediate product tends to decrease in response to a higher royalty rate. This effect may or may not overwhelm the positive effect of the elevated royalty rate on the final product price, so that the overall impact on the final product price is ambiguous.

Our paper is closest, both in terms of the industry analyzed and methodology, to Yang's (2020) empirical study of the U.S. smartphone and SoC markets. His main focus is on how a hypothetical vertical integration between a supplier-licensor (Qualcomm) and a final product manufacturer (HTC) affects innovation and welfare. In one of his counterfactual analyses, Yang (2020) assumes that the integrated firm (Qualcomm-HTC) loses all of its royalty revenues from rival final product manufactur-

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[7] They consider a vertical oligopoly model where the quantity of the final product (and by extension, the quantity of the upstream component) is fixed. This, in effect, assumes away anticompetitive quantity reductions.

[8] This assumption is also employed by Yang (2020). The various lawsuits faced by Qualcomm creates some doubt as to whether Qualcomm's royalty rates are FRAND-compliant, but it is nevertheless unlikely that the rates are set to maximize Qualcomm's profits.

ers after the merger.[9] In the resulting equilibrium, the SoC prices paid by Qualcomm's customers are slightly higher than under the status quo, but it is not clear how much of this is due to vertical foreclosure ("raising rivals' costs" by Qualcomm-HTC) and how much is due to the loss of royalty revenues.[10] In contrast to Yang (2020), we explicitly focus on the relationship between Qualcomm's royalty rates on the one hand, and the prices of SoCs and smartphones on the other. Our counterfactual analysis is designed to quantify the effect of a relatively small reduction in Qualcomm's royalty rate (enforced through government intervention), rather than the outright loss of royalty revenues. Our paper also differs from Yang (2020) in the way the SoC segment is modeled. Whereas Yang (2020) models it as a dominant-fringe market with Qualcomm as the dominant firm, we allow for strategic interaction among multiple SoC suppliers. This allows us to examine how the royalty rate reduction affected SoC pricing by both Qualcomm and its rivals.

Previous papers that have studied the Chinese smartphone market include Fan and Zhang (2022), which examines the price and welfare effects of a subsidy on handsets and Wang (2023), which looks at smartphone manufacturers' product portfolio choices. Our paper is differentiated from theirs through our focus on the upstream SoC segment and how it relates to the downstream smartphone market through Qualcomm's licensing practices.

Finally, our paper builds upon the empirical industrial organization literature on vertical oligopoly. Our basic modeling approach follows the dual-Bertrand structure of Berto Villas-Boas (2007) and Bonnet and Dubois (2010). Our novel contribution is to incorporate the royalty rate charged by one of the upstream suppliers, Qualcomm, into the structural model.

Road Map. The remainder of this paper is structured as follows. In section 2, we describe the licensing of standard-essential patents in the cellular communications area, focusing on the legal controversy surrounding Qualcomm's licensing practices and the resulting government intervention. After providing a brief description of the Chinese smartphone and SoC markets, we motivate our empirical analysis by presenting a theoretical model in which an intermediate product supplier-cum-technology licensor collects royalties from final product manufacturers. We use the model to show that an exogenous reduction in royalty rate has an ambiguous effect on the final product price.

Sections 3 through 6 cover our empirical analysis. Following a description of our data in section 3, we present our structural econometric model in section 4. Section 5 describes our estimation strategy and estimation results. Section 6 contains the results of our counterfactual analysis. Section 7 concludes.

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[9] This is presumably because the integrated firm's rivals in the downstream market move away from the cellular standard that relies on Qualcomm's SEPs.

[10] Yang (2020) also simulates a vertical integration scenario where Qualcomm-HTC maintains its royalty revenue. The counterfactual equilibrium involves higher SoC prices paid by Qualcomm's customers, but the increase seems slightly smaller than under the scenario where Qualcomm-HTC loses its royalty revenue.

2 Background and motivation

A Licensing of Standard-Essential Patents for Cellular Communications

Many high-tech industries are built upon innovations carried out by multiple entities. Such industries often require the standardization of technologies which allows different products and services to be mutually compatible. In the cellular communications sector, for instance, firms must coalesce around a given standard to allow their products to communicate with each other. To this end, second-generation ("2G") standards including GSM and cdmaOne were developed in the 1990s, followed by third-generation ("3G") standards including WCDMA, CDMA2000, and TD-SCDMA in the 2000s. Fourth-generation ("4G") standards were introduced in the late 2000s and one of them, LTE, became the dominant standard worldwide from the mid-2010s.[11]

SEPs that cover the technologies essential to implementing a standard are typically held by several different firms. This gives rise to two potential problems. First, individual SEP holders may gain the ability to "hold up" the implementation of the standard by refusing to license their patents, allowing them to demand excessively high royalties (Shapiro, 2000). This leads to the second problem, known as "royalty stacking", where the sum of the royalty rates of individual SEP holders becomes so high that implementation of the standard becomes economically infeasible (Lemley and Shapiro, 2007; Lerner and Tirole, 2004). To deal with these potential problems, the organizations that oversee the standardization process, called standard-setting organizations ("SSOs"), often restrict the licensing terms that SEP holders can set (Lemley, 2002).

In the case of SSOs overseeing cellular standards such as the Alliance for Telecommunication Industry Solutions ("ATIS"), Telecommunications Industry Association ("TIA"), and the European Telecommunications Standards Institute ("ETSI"), SEP holders are required to license their SEPs on FRAND terms.[12] The meaning of FRAND has not been sufficiently clarified by the SSOs, however, and this has led to numerous disputes involving SEP holders, their licensees, as well as antitrust agencies.

B Antitrust Scrutiny of Qualcomm's Licensing Practices

Our paper focuses on one particular set of disputes regarding cellular SEPs: those involving the licensing practices of Qualcomm Incorporated. Qualcomm is an American firm that holds a large number of SEPs for the 2G (cdmaOne), 3G (CDMA2000 and WCDMA), and 4G (LTE) cellular standards.[13,14] It is also a supplier of baseband processors and SoCs. While Qualcomm's cellular SEPs cover the technologies embodied in those chips, the company does not grant licenses for the SEPs to rival chipmakers. Rather, Qualcomm licenses its SEPs to handset manufacturers and collects royalties from them in terms of a fixed percentage of the handset's net wholesale price. Qualcomm's royalty rates on licenses for the cdmaOne, CDMA2000 and WCDMA standards are typically five percent (subject to discounts for specific licensees), while those for the LTE standard are between 3.5 and four percent.[15]

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[11] The fifth-generation ("5G") standard, which began deployment in 2019, is not covered in the dataset used for our analysis.

[12] Federal Trade Commission v. Qualcomm Inc., 411 F.Supp.3d 658 at 671-672 (N.D. Cal. 2019).

[13] The cdmaOne and CDMA2000 standards are sometimes jointly referred to as "CDMA".

[14] Regarding Qualcomm's SEPs in the 3G sphere, there has been a dispute between Qualcomm and its competitors on whether or not those SEPs cover the TD-SCDMA standard. See, for example, RCR Wireless News (2006).

[15] 411 F.Supp.3d 658 at 673. See also Yang (2020).

Legal Challenges Prior to the NDRC Intervention. Qualcomm's licensing practices were first challenged on antitrust grounds by Broadcom, another American chipmaker, in July 2005. Broadcom claimed that Qualcomm violated the antitrust laws by falsely promising to license its WCDMA SEPs on FRAND terms during the standardization process, only to charge excessive royalties once the industry became locked into the WCDMA standard. A federal district court ruled in favor of Qualcomm, but the U.S. Court of Appeals for the Third Circuit reversed and remanded the case to the district court, stating that Qualcomm's conduct may amount to a willful acquisition of monopoly power in violation of Section 2 of the Sherman Act.[16] The case never resulted in remedial action against Qualcomm's licensing practices because Broadcom and Qualcomm settled their lawsuit in 2009.[17]

Similar claims against Qualcomm were made by Broadcom, Nokia, and four other firms in a complaint filed with the European Commission in October 2005, and a formal investigation by the competition branch of the Commission began in October 2007. However, the investigation was closed in November 2019 before reaching any conclusion, after Qualcomm settled with each of the complainants.[18] Qualcomm also faced scrutiny from the South Korean and Japanese antitrust authorities in the late 2000s. It received a fine from the Korea Fair Trade Commission (KFTC) in 2010 as well as a cease-and-desist order from the Japan Fair Trade Commission (JFTC) in 2009. However, these actions did not require Qualcomm to fundamentally alter its licensing practices.[19]

The NDRC Intervention. The National Development and Reform Commission ("NDRC"), which was one of the Chinese government's competition agencies at the time, launched an investigation into Qualcomm's licensing practices in November 2013. In February 2015, the NDRC announced its decision finding that Qualcomm violated the country's Anti-Monopoly Law by abusing its SEPs for the cdmaOne, CDMA2000, WCDMA and LTE standards, as well as its dominant position in the markets for "baseband chips" compliant with the WCDMA and LTE standards.[20] According to the NDRC, certain elements of Qualcomm's licensing practices allowed it to charge excessive royalty rates. These include: (i) using the net wholesale price of the handset as the royalty base rather than the component price; (ii) failing to exclude expired SEPs from the bundle of licensed patents; (iii) bundling non-wireless SEPs toghether with wireless SEPs; (iv) requiring licensees to provide royalty-free cross-licenses of their patents to Qualcomm and its customers; and (v) conditioning the supply of Qualcomm's chips on an agreement not to dispute its licensing terms (i.e., the "no license, no chips" policy). According to the NDRC's theory of harm, elements (i) through (iv) worked to elevate the effective royalty rate that Qualcomm could charge, while element (v) ensured that Qualcomm maintained a strong bargaining position vis-à-vis licensees. The NDRC claimed that the unfairly high royalty rates charged by Qualcomm caused handset manufacturers' costs to increase, which in turn

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[16] Broadcom Corporation v. Qualcomm Inc., 501 F.3d 297 (3rd Cir. 2007)

[17] See Qualcomm Incorporated. (2009, April 26). *Qualcomm and Broadcom Reach Settlement and Patent Agreement* [Press release].

[18] See Qualcomm Incorporated. (2010, January 27). *Form 10-q.* U.S. Securities and Exchange Commission. `https://www.sec.gov/Archives/edgar/data/804328/000095012310005721/a54942e10vq.htm`

[19] The JFTC order was eventually revoked in 2019 after a successful administrative appeal by Qualcomm. See Qualcomm Incorporated. (2019, March 14). *JFTC Revokes Order, Finds Qualcomm Licensing Program Lawful* [Press release].

[20] See National Development and Reform Commission Administrative Sanction Decision No. 1 [2015], dated February 9, 2015. While not explicitly stated in the decision, "baseband chips" include both baseband processors and SoCs.

caused handset prices to increase and harmed consumers.[21] The NDRC's decision did not provide any empirical evidence to support its claims regarding the effect of Qualcomm's practices on handset prices.

Unlike in other jurisdictions where it faced antitrust scrutiny, Qualcomm did not challenge the NDRC's findings and agreed to pay a fine of 6.088 billion Chinese RMB (approximately $992 million at the exchange rate in February 2015[22].). It also agreed to alter its licensing practices in the following manner: (a) unbundle its valid wireless SEPs from expired patents and non-wireless SEPs before licensing them; (b) not require licensees to grant royalty-free cross-licenses; (c) not condition the supply of chips on an agreement to the licensing terms; and (d) lower the royalty base to 65 percent of the net wholesale price of handsets.[23] According to legal commentators, a particularly notable aspect of the decision was the mandated change in royalty base, which is effectively the same as a forced reduction in royalty rates. Assuming handset prices remained constant (an assumption that we do not maintain in our analysis), the royalty rate reduction would have caused a 35 percent decrease in Qualcomm's royalty revenue. This action was notable both because it was the first instance of a forcible reduction in Qualcomm's royalty rates, and because Qualcomm was allowed to keep using the handset price (albeit a smaller proportion of it) as the royalty base.[24]

Further Antitrust Challenges. The NDRC decision was quickly followed by a March 2015 announcement by the KFTC that it was starting a new investigation into Qualcomm's licensing practices. A decision was announced in January 2017, finding that Qualcomm violated South Korea's Monopoly Regulation and Fair Trade Act and imposing a 1.03 trillion Korean won (approximately $890 million at the exchange rate in January 2017[25]) fine on the firm. The KFTC found the following elements to be illegal: (i) refusal to license SEPs to rival chipmakers; (ii) the "no license, no chips" policy; and (iii) requirement of royalty-free cross-licenses from licensees. The remedies ordered by the KFTC include a requirement for Qualcomm to enter into good-faith licensing negotiations with rival chipmakers. Qualcomm filed suit in the Seoul High Court to annul the KFTC decision but the court upheld most of it, including the order to negotiate with chipmakers. Qualcomm's subsequent appeal to the Supreme Court resulted in an affirmation of the lower court's ruling in April 2023.[26]

In the U.S., the FTC brought suit against Qualcomm in January 2017, claiming that its licensing practices for SEPs led to elevated royalty rates. According to the FTC, this acted as a "tax" on chips made by Qualcomm's rivals, which had the dual effect of excluding those chipmakers from the market for baseband chips (both baseband processors and SoCs), and causing handset manufacturers to set higher prices at the expense of consumers. The U.S. District Court for the Northern District of California found in favor of the FTC, ruling in May 2019 that Qualcomm's royalty rates were unreasonably high, and that as a result, rival chipmakers were being excluded from the market.[27] The

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[21] See Section II(I) of the NDRC Decision.

[22] IMF, Exchange Rate Archives by Month

[23] See Qualcomm Incorporated. (2019, February 9). *Qualcomm and China's National Development and Reform Commission Reach Resolution: NDRC Accepts Rectification Plan* [Press release].

[24] See, for example, Cleary Gottlieb Steen & Hamilton LLP. (2015, March 16) *China's NDRC Concludes Qualcomm Investigation, Imposes Changes in Licensing Practices* [Memorandum].

[25] IMF, Exchange Rate Archives by Month

[26] See Qualcomm Incorporated. (2023, May 3). *Form 10-q.* U.S. Securities and Exchange Commission. `https://www.sec.gov/Archives/edgar/data/0000804328/000080432823000023/qcom-20230326.htm`

[27] *FTC v. Qualcomm Inc.*, 411 F.Supp.3d 658 (N.D.Cal. 2019).

district court also found that Qualcomm had a duty to license its SEPs to rival chipmakers and that failure to do so violated Section 2 of the Sherman Act.[28]

Following an appeal by Qualcomm, the U.S. Court of Appeals for the Ninth Circuit reversed the district court decision in August 2020. A key element of the appellate court decision was the finding that Qualcomm did not have an "antitrust duty to deal" with its competitors – i.e., it was not obligated to license its SEPs to rival chipmakers.[29] Interestingly, the decision did not rule out the possibility that Qualcomm's licensing practices had an exclusionary effect on rival chipmakers through a "margin squeeze", admitting the possibility that "Qualcomm uses its licensing royalties to charge anticompetitive, ultralow prices on its own modem chips – pushing out rivals by squeezing their profit margins".[30] Nevertheless, the appellate court rejected the FTC's assertion of antitrust liability on the grounds that (i) there was no evidence that Qualcomm engaged in predatory pricing in the baseband chip market,[31] and (ii) there was no evidence that Qualcomm applied discriminatorily higher royalty rates to handset manufacturers using non-Qualcomm chips.[32]

C Structure of the Chinese Smartphone and SoC Markets

The Chinese smartphone and SoC markets were characterized by the coexistence of multiple cellular standards during the early 2010s, as can be seen from Figure 1(a) which shows the distribution of smartphone models, and Figure 2(a) which shows the distribution of units sold. The latter figure shows how the 2G GSM standard quickly lost market share during this period, while the three 3G standards – CDMA2000, WCDMA and TD-SCDMA – each gained market share until they were overtaken by LTE (4G) from 2014 onward.

Among the 3G standards, Qualcomm held a dominant share of SEPs for CDMA2000, while those for WCDMA were more evenly held by Qualcomm and several other firms including Nokia, Ericsson, InterDigital (a so-called "non-practicing entity" that asserts the rights on patents purchased from other firms), and LG Electronics (Yang and Jung, 2014). TD-SCDMA is a China-specific standard developed jointly by the Chinese Academy of Telecommunications Technology and Siemens AG. While Qualcomm has claimed that its patents cover TD-SCDMA technology, it is not clear whether it charges royalties on handsets that solely employ the TD-SCDMA standard.[33] For the 4G LTE standard, Qualcomm is one of the leading SEP holders along with Nokia, Ericsson, Samsung and Huawei.[34]

Figures 1(b) and 2(b) demonstrate how Qualcomm maintained a significant share of the Chinese SoC market throughout the 3G and 4G eras. Measured in terms of the number of smartphone models using its chips, Qualcomm's market share has been matched by that of M; the share of other chipmakers have remained much smaller (Figure 1(b)). The picture is somewhat different when shares are measured in terms of the number of smartphone units sold (Figure 2(b)). Here, Qualcomm has

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[28] The district court further found that Qualcomm's exclusive dealing agreements with one of its customers, Apple, violated Sections 1 and 2 of the Sherman Act.

[29] See *FTC v. Qualcomm Inc.*, 969 F.3d 974 (9th Cir. 2020). This ruling was based on the observation that under U.S. case law, an antitrust duty to deal is found only in circumstances where a firm's refusal to deal is purely motivated by exclusionary intent. See *Aspen Skiing Co. v. Aspen Highlands Skiing Corp.*, 472 U.S. 585 (1985).

[30] *FTC*, 969 F.3d, at 1000-1001.

[31] *FTC*, 969 F.3d, at 1001.

[32] *FTC*, 969 F.3d, at 996-997.

[33] See RCR Wireless News (2008) on the lack of clarity regarding Qualcomm's royalty revenues in China from TD-SCDMA handsets.

[34] See plaintiffs' second amended complaint in *In re Qualcomm Antitrust Litigation* (N.D. Cal. 2023), available at `https://storage.courtlistener.com/recap/gov.uscourts.cand.309826/gov.uscourts.cand.309826.899.0.pdf`

maintained the largest share but there are two rival firms in addition to M with significant market shares. S maintained a fairly large market share during the 3G period, while H has rapidly gained market share from around 2015, just as 3G standards were being replaced by LTE. This period also coincides with the NDRC intervention in February 2015.

Figures 1(c) and 2(c) describes the structure of the Chinese smartphone market. Figure 2(c) shows that during the observed period, there were seven leading smartphone manufacturers.[35] Initially, S1 (which belongs to the same corporate group as chipmaker S) had the largest market share, but it was gradually overtaken by the company owning brands O1 and V1, the company owning brands H1 and H2, and A1. Smaller brands (the "Others" category) also served a large proportion of demand up to 2014. From 2015 onward, the market has become more concentrated, with only four manufacturers – A1, the owner of brands H1 and H2, the owner of brands O1 and V1, and M1 – maintaining significant market shares, and the combined share of smaller brands shrinking over time. Nevertheless, the combined presence of smaller brands has remained large when measured in terms of the number of models (Figure 1(c)). As can be seen from Figure 1(d), more than half of all smartphone models were supplied by smaller brands whose maximum annual sales volume during 2011-2018 was less than 1 million units.

The fragmented structure of the smartphone market, as well as the vertical structure of the industry, may have contributed to the relatively competitive nature of the Chinese SoC market. Of the seven leading smartphone manufacturers, six have procured SoCs from both Qualcomm and M, providing both chipmakers with a large customer base. In addition, the company that owns the H1 and H2 smartphone brands is also the parent company of SoC supplier H. This has likely provided an assured demand for the chips manufactured by H.

Against this backdrop, an important question is whether, and to what extent, the NDRC's intervention affected the prices and profitability of the SoC manufacturers. Another relevant question is how the NDRC intervention, in conjunction with changes in SoC prices, affected the prices of smartphones. Before addressing these questions empirically, we use a theoretical model to sort out the economic forces that could drive such price changes.

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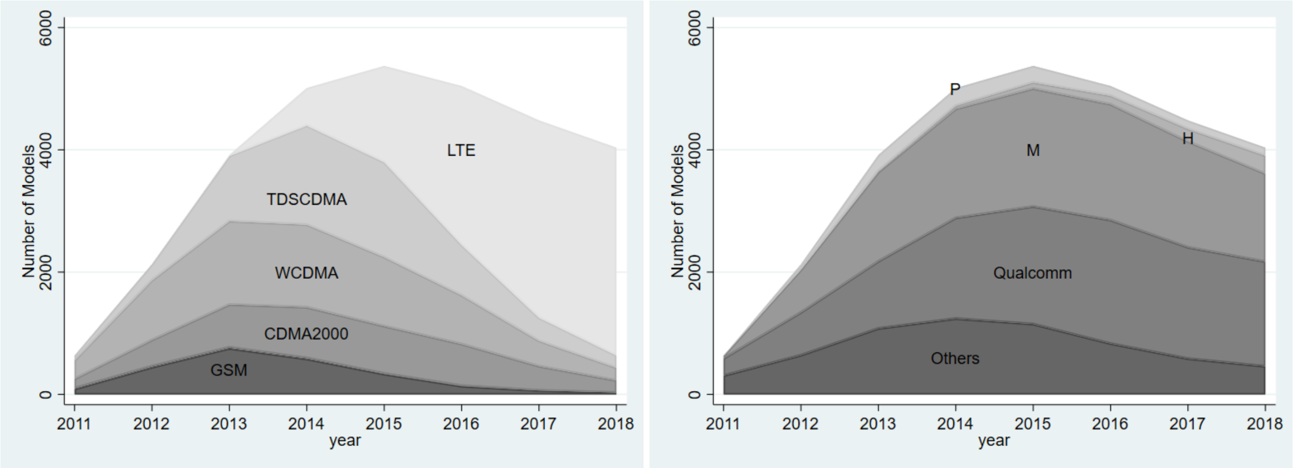
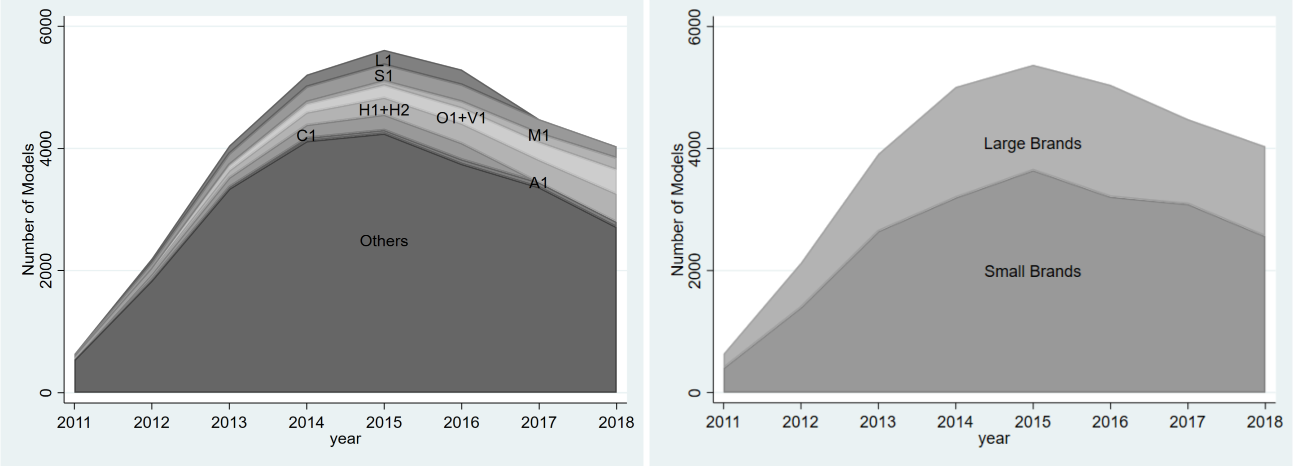
[35] The seven smartphone manufacturers appearing in Figures 1(c) and 2(c) are those with the largest cumulative sales volumes during 2011-2018. The abbreviated names appearing in the figures (e.g., A1, H1) represent "brands". In this paper, smartphone brands correspond to smartphone manufacturers except for the following two cases: brands H1 and H2 are owned by the same company, and brands O1 and V1 are owned by the same company.

Figure 1: Distribution of Smartphone Models in China, 2011-2018



(a) By cellular standard

(b) By SoC supplier

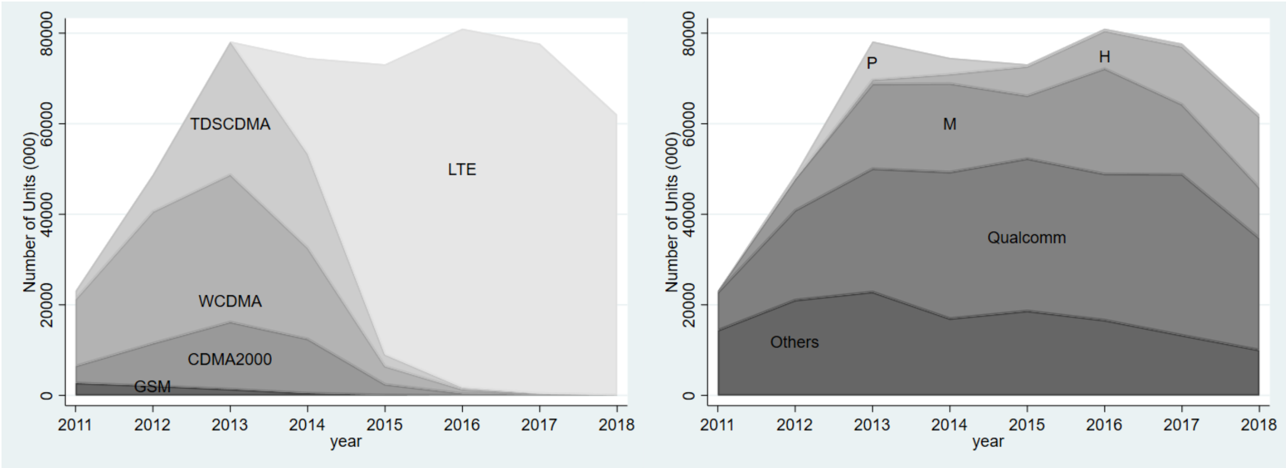


(c) By smartphone manufacturer

(d) Large vs. small smartphone brands

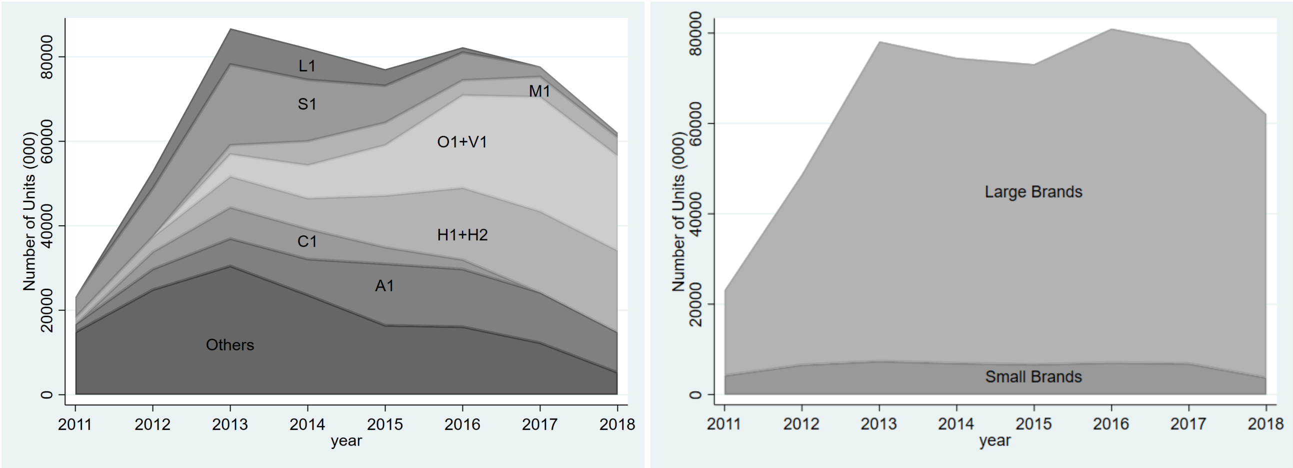
Source: Authors' calculations based on GfK data.
Note: "Large" brands are defined as those having maximum annual sales volume at or above 1 million units during 2011-2018; remaining brands are categorized as "small." Brands H1 and H2 are combined because they are owned by the same company. Brands O1 and V1 are combined for the same reason.

Figure 2: Distribution of Smartphones Units Sold in China, 2011-2018



(a) By cellular standard

(b) By SoC supplier



(c) By smartphone manufacturer

(d) Large vs. small smartphone brands

Source: Authors' calculations based on GfK data.
Note: "Large" brands are defined as those having maximum annual sales volume at or above 1 million units during 2011-2018; remaining brands are categorized as "small." Brands H1 and H2 are combined because they are owned by the same company. Brands O1 and V1 are combined for the same reason.

D Theoretical Motivation

The economic rationale for the NDRC intervention was that Quacomm's licensing practices for SEPs led to elevated royalty rates, which in turn caused (i) an increase in smartphone manufacturers' costs and (ii) an increase in smartphone prices. To investigate the validity of these concerns, we use a simple theoretical model to describe how the supplier of an upstream intermediate product, who also receives royalty payments from manufacturers of the downstream final product, responds to an exogenous change in the royalty rate. Both the downstream and upstream markets are assumed to be duopolies. Whereas the downstream firms supply differentiated products, the upstream product is assumed to be homogenous. One of the upstream firms ("supplier-licensor") holds a portfolio of essential patents for the final product, and licenses it out for a royalty rate of $\phi \in [0, \bar{\phi}]$ on final product sales (the value of $\bar{\phi} < 1$ will be specified shortly). It is assumed that ϕ is determined exogenously to satisfy the FRAND requirements stipulated by SSOs and/or courts. A change in ϕ is assumed occur as a result of intervention by a government agency (such as the NDRC) or a court ruling.

Each downstream firm $m \in \{1, 2\}$ supplies a single final product to consumers. The demand function for firm m's product is given by $Q_m(p_m, p_{m'}) = a - bp_m + dp_{m'}$, where $m' = 3 - m$ and $0 < d < b/2$. For simplicity, we assume that downstream firms' marginal cost, excluding the cost of the intermediate product, is zero.

Assuming that the downstream firms compete in prices, firm m's profit maximization problem is

$$\max_{p_m} [(1-\phi)p_m - w](a - bp_m + dp_{m'}),$$

where w denotes the market price of the intermediate product. Firm m's first-order condition for profit maximization yields the reaction function for the downstream market:

$$p_m = R^d(p_{m'}) = \frac{a + dp_{m'}}{2b} + \frac{w}{2(1-\phi)}. \tag{1}$$

Solving the system of equations formed by the two reaction functions, we obtain the equilibrium price for each final product, expressed as a function of w and ϕ:

$$p_m^*(w, \phi) = \frac{1}{2b - d}\left(a + \frac{bw}{1-\phi}\right), \; m = 1, 2. \tag{2}$$

Plugging these into the demand function, we obtain firm m's derived demand function for the intermediate product as

$$q_m(w, \phi) = \frac{b}{2b - d}\left(a - \frac{b-d}{1-\phi}w\right). \tag{3}$$

We now turn to the upstream market, where the suppliers of the intermediate product are assumed to engage in price competition so that the firm offering the lower price captures the entire market demand. (In the event of a tie, we assume that the two suppliers split the market demand evenly.) Denoting the supplier-licensor by l and the other upstream firm by n, n's profit maximization problem can be written as

$$\max_{w_n} \sum_{m=1,2} (w_n - c) q_{mn}^r(w_n, w_l, \phi),$$

where w_n denotes supplier n's price, c is the marginal cost of supplying the intermediate product (assumed to be common to both suppliers), and the residual demand function $q^r_{mn}(w_n, w_l, \phi)$ is defined as follows (and vice versa for $q^r_{ml}(w_l, w_n, \phi)$):

$$q^r_{mn}(w_n, w_l, \phi) = \begin{cases} q_m(w_n, \phi) & \text{if } w_n < w_l \\ \frac{q_m(w_n,\phi)}{2} & \text{if } w_n = w_l \\ 0 & \text{otherwise.} \end{cases}$$

Let us assume that $b - d < \frac{a}{c}$ and $\bar{\phi} = 1 - \frac{c(b-d)}{a}$. Then, due to the discontinuous jump in its residual demand function at $w_n = w_l$, firm n has an incentive to undercut firm l's price by a small amount as long as $c < w_l \leq w^*_n(\phi)$, where $w^*_n(\phi) = \frac{c}{2} + \frac{a(1-\phi)}{2(b-d)}$ is firm n's profit-maximal price as a monopolist in the upstream market.[36] If firm n expects $w_l = c$, it will set the same price and serve half the market demand. Thus, firm n's reaction function in the upstream market is

$$w_n = R^u_n(w_l) = \begin{cases} c & \text{if } w_l \leq c \\ w_l - \epsilon & \text{if } c < w_l \leq w^*_n(\phi) \\ w^*_n(\phi) & \text{if } w_l > w^*_n(\phi) \end{cases} \tag{4}$$

for some small ϵ.

The supplier-licensor's profit includes not only its profit from intermediate product sales but also royalty revenues from downstream firms. Its profit maximization problem is therefore

$$\max_{w_l} \sum_{m=1,2} (w_l - c) q^r_{ml}(w_l, w_n, \phi) + \phi p^*_m\left(\min\{w_l, w_n\}, \phi\right) q_m\left(\min\{w_l, w_n\}, \phi\right),$$

where the second additive term inside the summation represents the royalty revenue from each downstream firm. To construct the supplier-licensor's reaction function, we first derive its profit-maximal price as a monopolist:

$$\begin{aligned} w^*_l(\phi) &= \arg\max_w \sum_{m=1,2} (w - c) q_m(w, \phi) + \phi p^*_m(w, \phi) q_m(w, \phi) \\ &= \arg\max_w \frac{2b}{2b-d}\left(a - \frac{b-d}{1-\phi} w\right)\left[w - c + \frac{\phi}{2b-d}\left(a + \frac{bw}{1-\phi}\right)\right] \\ &= \frac{(1-\phi)\left\{c(b-d)(2b-d) + a\left[2(b-d)(1-\phi) + d\right]\right\}}{2(b-d)\left[(b-d)(1-\phi) + b\right]}, \end{aligned}$$

where the second line makes use of equations (2) and (3) as well as the assumed symmetry between the two downstream firms. It is straightforward to check that $w^*_l(\phi)$ is a decreasing function of $\phi \in [0, \bar{\phi}]$.[37] $w^*_l(\phi)$ may be above or below c depending on the value of ϕ, as can be seen from the numerical example presented in Figure 3. We define $\hat{\phi}$ as the value of ϕ at which $w^*_l(\phi) = c$ is attained.

For $\phi \in [0, \hat{\phi})$, firm l's reaction function is given by

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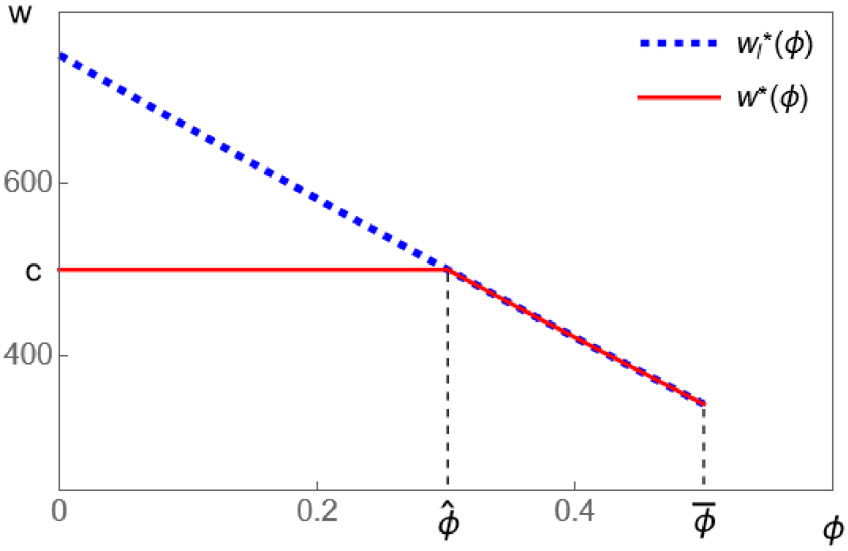
[36] Our assumptions regarding a, b, c, d and $\bar{\phi}$ guarantee that $w^*_n > c$.

[37] Its first-order derivative is

$$\frac{dw^*_l(\phi)}{d\phi} = \frac{-(b-d)\left[4a(b-d)^2(1-\phi)^2 + 8ab(b-d)(1-\phi) + 2bc(b-d)(2b-d) + 2abd\right]}{\left\{2(b-d)\left[(b-d)(1-\phi) + b\right]\right\}^2} < 0.$$

Figure 3: Equilibrium Intermediate Product Price



Note: The graphs represent the supplier-licensor's monopoly price (dotted line) and equilibrium price (solid line) under the following parameter values: $a = 20,000, b = 30, c = 500, d = 10$.

$$w_l = R_l^u(w_n) = \begin{cases} c & \text{if } w_n \leq c \\ w_n - \epsilon & \text{if } c < w_n \leq w_l^*(\phi) \\ w_l^*(\phi) & \text{if } w_n > w_l^*(\phi), \end{cases}$$

whereas for $\phi \in [\hat{\phi}, \bar{\phi}]$, firm l simply sets $w_l = w_l^*(\phi)$. Combining this with firm n's reaction function in equation (4), the equilibrium price for the intermediate product is obtained as follows:

$$w^*(\phi) = \begin{cases} c & \text{if } \phi \in [0, \hat{\phi}) \\ w_l^*(\phi) & \text{if } \phi \in [\hat{\phi}, \bar{\phi}]. \end{cases}$$

This result, which is also shown in Figure 3, implies that the equilibrium price for the intermediate product is a weakly decreasing function of the royalty rate charged to downstream firms. This negative relationship between an ad valorem fee charged on downstream firms (royalty rate) and the price charged by upstream firms (intermediate product price) has previously been noted in the literature on revenue-sharing contracts (e.g., Cachon and Lariviere, 2005).

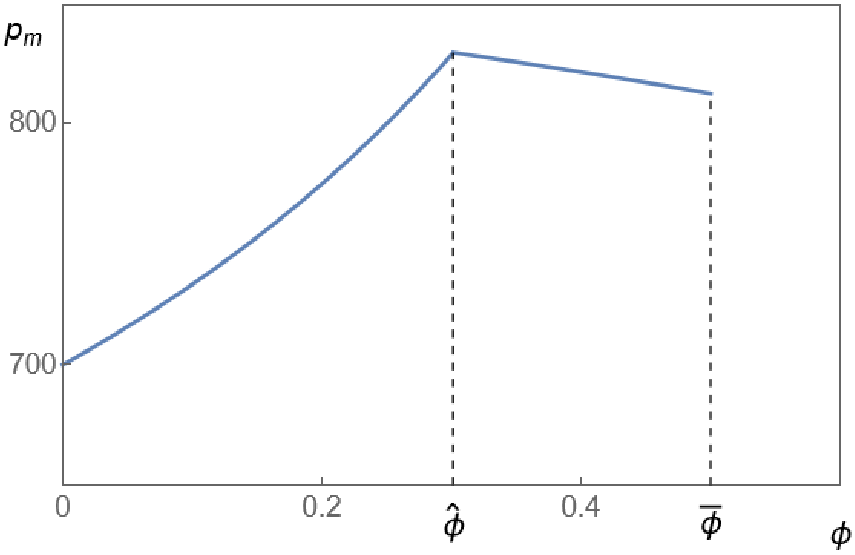
To examine the effect of a change in the royalty rate on downstream prices, we first consider the case of $\phi \in [0, \hat{\phi})$. In this case, each equilibrium downstream price is given by $p_m^*(c, \phi) = \frac{1}{2b-d}\left(a + \frac{bc}{1-\phi}\right)$ and its partial derivative with respect to ϕ is

$$\frac{\partial p_m^*(c, \phi)}{\partial \phi} = \frac{bc}{(2b-d)(1-\phi)^2} > 0.$$

Thus, an increase in the royalty rate causes an increase in downstream prices.

In the case of $\phi \in [\hat{\phi}, \bar{\phi}]$, the equilibrium downstream price is given by $p_m^*(w_l^*(\phi), \phi) = \frac{1}{2b-d}\left(a + \frac{bw_l^*(\phi)}{1-\phi}\right)$ and its derivative with respect to ϕ is

Figure 4: Equilibrium Final Product Price



Note: The graph represent the final product price under the following parameter values: $a = 20,000, b = 30, c = 500, d = 10$.

$$\begin{aligned}\frac{dp_m^*(w_l^*(\phi),\phi)}{d\phi} &= \frac{\partial p_m^*(w_l^*(\phi),\phi)}{\partial w}\frac{dw_l^*(\phi)}{d\phi} + \frac{\partial p_m^*(w_l^*(\phi),\phi)}{\partial \phi} \\ &= \frac{b}{(2b-d)(1-\phi)}\left[\frac{dw_l^*(\phi)}{d\phi} + \frac{w_l^*(\phi)}{1-\phi}\right].\end{aligned} \tag{5}$$

The term in square brackets is calculated as

$$\frac{dw_l^*(\phi)}{d\phi} + \frac{w_l^*(\phi)}{1-\phi} = -\frac{(2b-d)[a-c(b-d)](1-\phi)}{2\left[(b-d)(1-\phi)+b\right]^2},$$

which is negative due to our assumption that $b - d < \frac{a}{c}$. Thus, we obtain the following result, which says that an increase in the royalty rate causes a *decrease* in downstream prices:

$$\frac{dp_m^*(w_l^*(\phi),\phi)}{d\phi} < 0. \tag{6}$$

The above results can be confirmed from the numerical example presented in Figure 4, showing that the equilibrium downstream price is increasing in ϕ up to $\phi = \hat{\phi}$, and decreasing in ϕ thereafter. This suggests that an exogenous reduction in the royalty rate, such as the one imposed by the NDRC in the Chinese smartphone market, can have a negative or positive effect on the final good price. This ambiguity arises because a reduction in ϕ has two opposing effects. On the one hand, the reduction in ϕ increases the marginal revenue of smartphone manufacturers, which incentivizes them to increase supply by lowering price. This can be seen by partially differentiating equation (2) with respect to ϕ to obtain $\frac{\partial p_m}{\partial \phi} = \frac{bw}{(2b-d)(1-\phi)^2} > 0$. Another interpretation of this effect is a reduction in the "effective marginal cost" of smartphone manufacturers. This can be seen by rewriting firm m's profit in the downstream market as $(1-\phi)(p_m - \frac{w}{1-\phi})(a - bp_m + dp_{m'})$, where $\frac{w}{1-\phi}$ can be thought of as an effective marginal cost which increases with ϕ. On the other hand, the reduction in ϕ may cause an increase in the intermediate good price, as shown in Figure 3. This raises downstream firms' marginal costs, exerting upward pressure on the price of final products. The existence of these opposing effects imply that the directional impact of an exogenous reduction on smartphone prices remains an empirical question.

As for the validity of the NDRC's theory of harm mentioned at the beginning of this section, there is insufficient information in the agency's decision to support its claim that Qualcomm's elevated royalty rates caused smartphone manufacturers' costs to increase. On the one hand, the elevated royalty rates are likely to have increased smartphone manufacturers' perceived marginal costs, an effect that has been claimed in the NDRC decision as well as in the FTC's complaint against Qualcomm. On the other hand, the elevated royalty rates may have reduced SoC prices (as suggested by Figure 3), both for Qualcomm and rival chipmakers, exerting downward pressure on smartphone manufacturers' marginal costs.[38] Thus, it appears that the NDRC's claim – that Qualcomm's elevated royalty rates caused an increase in smartphone prices – was made without accounting for all the economic forces at play.

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[38] Importantly, this possibility was mentioned in the appellate court decision in *FTC*, 969 F.3d, at 1000-1001.

3 Data

Our data are sourced from GfK China's Market Audit Survey for the Chinese smartphone market. The original dataset covers all smartphones sold in 20 cities as well as online between 2011 and 2018.[39] In our empirical analysis, we restrict attention to sales at physical stores and do not use data from online sales.[40] We also do not use data for the two cities of Shenzhen and Guangdong, because the sales volumes in these cities were extremely large – almost 4 times their population. It is possible that sales figures for these cities contain de facto wholesale transactions which were resold to other regions of China or exported

The resulting dataset, which we used to estimate demand, covers 675 smartphone manufacturers, 9,593 smartphone models, 22 processor suppliers, and 438 processor models. For each smartphone model, we have information on the number of units sold, average price, and various attributes such as cellular standard(s), type of operating system, display size, and the identity of the SoC or processor installed (supplier and model). Summary statistics of the data are presented in Table 1. All monetary figures were deflated to 2011 prices using the consumer price index.

Table 1: Summary Statistics

	Mean	S.D.	Min	Max
Sales Units ('000)	1.64	8.27	0.00	1351.3
Price (RMB in 2011 prices)	1344	1322	60	27,999
cdmaOne	0.11	0.32	0	1
CDMA2000	0.39	0.49	0	1
WCDMA	0.51	0.50	0	1
TD-SCDMA	0.52	0.50	0	1
LTE	0.44	0.50	0	1
Display Size (inch)	4.63	0.84	1	6.98
OS:iOS	0.02	0.14	0	1
OS:Android	0.94	0.25	0	1
OS:Windows	0.02	0.15	0	1
OS:Symbian	0.01	0.11	0	1
OS:Other	0.01	0.09	0	1
Number of observations (model × city × year)	270,301			
Number of markets (city × year)	168			

Source: Authors' calculation based on GfK data.

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[39] Geographical distribution of our dataset does not fail to recover the distribution at the national level. The Chinese Income Household Project dataset, a representative panel household survey in China, is carefully designed to recover the distribution of income and assets in China. The 20 cities in our dataset consist of CHIPS target provinces and nontarget one as follows: Beijing(CHIPS), Changsha(CHIPS), Chengdu(CHIPS), Chongqing(CHIPS), Dongguan(CHIPS), Guangzhou(CHIPS), Harbin, Hefei(CHIPS), Kunming(CHIPS), Nanjing(CHIPS), Nanning, Ningbo, Shanghai, Shenyang(CHIPS), Shenzhen(CHIPS), Shijiazhuang, Suzhou(CHIPS), Tianjin, Xiamen and Xian. We conducted t-tests at the mean and variance ratios tests with regard to average wage, population, smartphone prices, and smartphone price-wage ratio, then found no significant differences existed except a t-test of smartphone price-wage ratio. We can regard that our geographical distribution in our dataset follows that of the CHIPS survey and, therefore, that of a nation.

[40] While products sold online may compete to some extent with those sold in physical stores, we do not have information to connect individual online purchases to specific cities. We therefore assume that online and physical stores constitute separate markets and focus our attention on the latter.

4 Econometric Model

A Smartphone Demand

We assume that in each period, consumers choose whether or not to purchase a smartphone, and if they do, the smartphone product generating the highest utility is chosen. The conditional indirect utility u_{ijt} of consumer i purchasing product j in market t is specified as

$$u_{ijt} = -\alpha p_{jt} + \beta' x_{jt} + \xi_{jt} + \nu_{ijt}, \tag{7}$$

where p_{jt} is the price of product j in market t, x_{jt} is the vector of observable attributes of product j in market t, ξ_{jt} denotes the effect of unobserved product characteristics, and ν_{ijt} is an error term specific to each consumer. x_{jt} contains observed product characteristics as well as dummy variables representing combinations of smartphone brands and SoC suppliers. In the following, we use the shorthand $\delta_{jt} := -\alpha p_{jt} + \beta' x_{jt} + \xi_{jt}$ to denote the portion of indirect utility that does not vary across consumers, and call it "mean utility".

We assume a two-level choice structure, where products are grouped into generations of cellular standards, as well as into brand types within each generation (see Figure 5). To estimate the demand system, we assume that the error term ν_{ijt} has a three-component structure conforming to the two-level nested logit model.[41] Suppose that product j belongs to a cellular standard of generation $g \in \{2, 3, 4\}$ and that its brand is of type $b \in \{\text{large}, \text{small}\}$, where a "large" brand is defined as one whose maximum annual sales volume during 2011-2018 was 1 million units or more. Suppressing the consumer and market subscripts for brevity, we assume that ν_j is structured as follows:[42]

$$\nu_j = \varepsilon_g + (1-\sigma_1)\varepsilon_{gb} + (1-\sigma_1)(1-\sigma_2)\varepsilon_{gbj}. \tag{8}$$

For notational convenience, we use the shorthand $1 - \lambda := (1-\sigma_1)(1-\sigma_2)$, and assume that σ_1 and σ_2 both lie on the unit interval. This implies that $0 \leq \sigma_1 \leq \lambda \leq 1$. The product-specific error component ε_{gbj} is assumed to be i.i.d. with a standard Gumbel distribution. The other two error components are assumed to have specific distributions that lead to the two-level nested logit model.[43] λ represents the degree to which a consumer's unobserved preference for smartphone products are correlated within the same brand type for a given generation, while σ_1 represents the degree to which unobserved preferences are correlated within the same generation.[44]

Under our distributional assumptions, an individual consumer's choice probability of smartphone product j, conditional on the consumer choosing generation g and brand type b, is derived as

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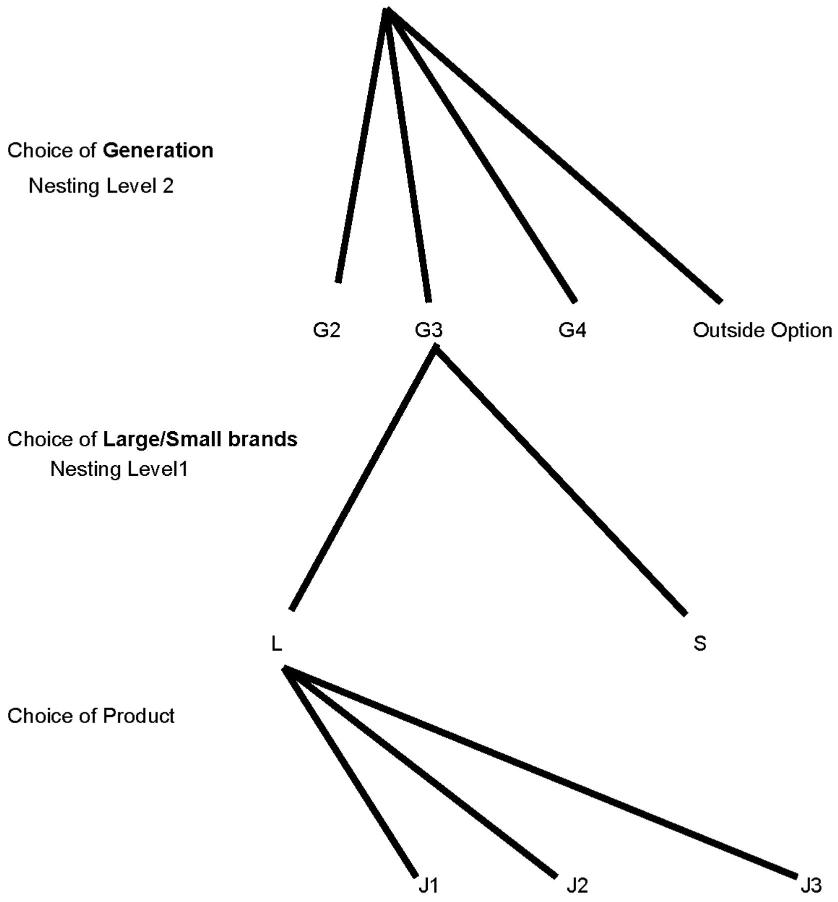
[41] Other papers that use the two-level nested logit model include Verboven (1996), Chatterjee, Kubo, and Pingali (2015), Björnerstedt and Verboven (2016), and Ciliberto, Moschini, and Perry (2019).

[42] This notation partly follows Ben-Akiva and Lerman (1985). Each error component is assumed to vary across consumers and markets.

[43] Specifically, we assume ε_{gb} is distributed such that $(1-\sigma_1)\varepsilon_{gb} + \max_{j' \in \mathcal{J}_{gb}}[\delta_{j'} + (1-\lambda)\varepsilon_{gbj'}]$ is i.i.d. Gumbel with location and scale parameters $\left(I_{gb},\ \frac{1}{1-\sigma_1}\right)$, where I_{gb} is the inclusive value for brand b in generation g, as defined in equation (10). We also assume ε_g is distributed such that $\varepsilon_g + \max_{b' \in \mathcal{B}_g}\left\{(1-\sigma_1)\varepsilon_{gb'} + \max_{j' \in \mathcal{J}_{gb'}}[\delta_{j'} + (1-\lambda)\varepsilon_{gb'j'}]\right\}$ is i.i.d. Gumbel with location and scale parameters $(I_g,\ 1)$, where I_g is the inclusive value for generation g, as defined in equation (11).

[44] From equation (8), we see that ν_j is perfectly correlated within the same brand type and generation when $\lambda = 1$, with the correlation decreasing as λ approaches zero. Similarly, ν_j is perfectly correlated within the same generation when $\sigma_1 = 1$, but the correlation drops as σ_1 falls toward zero.

Figure 5: Nesting Structure of Demand Model



$$s_{j|gb} = \frac{\exp\left(\frac{\delta_j}{1-\lambda}\right)}{\sum_{j' \in \mathcal{J}_{gb}} \exp\left(\frac{\delta_{j'}}{1-\lambda}\right)},$$

where $\mathcal{J}_{gb}$ is the set of all products belonging to generation g and brand type b. The probability that brand type b is chosen, conditional on generation g being chosen, is derived as

$$s_{b|g} = \frac{\left[\sum_{j' \in \mathcal{J}_{gb}} \exp\left(\frac{\delta_{j'}}{1-\lambda}\right)\right]^{1-\sigma_2}}{\sum_{b' \in \mathcal{B}_g} \left[\sum_{j' \in \mathcal{J}_{gb'}} \exp\left(\frac{\delta_{j'}}{1-\lambda}\right)\right]^{1-\sigma_2}},$$

where $\mathcal{B}_g$ is the set of all brand types in generation g. Finally, the probability of generation g being chosen is

$$s_g = \frac{\left\{\sum_{b' \in \mathcal{B}_g} \left[\sum_{j' \in \mathcal{J}_{gb'}} \exp\left(\frac{\delta_{j'}}{1-\lambda}\right)\right]^{1-\sigma_2}\right\}^{1-\sigma_1}}{1 + \sum_{g' \in \mathcal{G}} \left\{\sum_{b' \in \mathcal{B}'_g} \left[\sum_{j' \in \mathcal{J}_{g'b'}} \exp\left(\frac{\delta_{j'}}{1-\lambda}\right)\right]^{1-\sigma_2}\right\}^{1-\sigma_1}},$$

where $\mathcal{G}$ is the set of all generations. Combining these results, the unconditional market share of smartphone product j is expressed as follows:

$$s_j = \frac{\exp\left(\frac{\delta_j}{1-\lambda}\right)}{\sum_{j'\in\mathcal{J}_{gb}} \exp\left(\frac{\delta_{j'}}{1-\lambda}\right)} \times \frac{\left[\sum_{j'\in\mathcal{J}_{gb}} \exp\left(\frac{\delta_{j'}}{1-\lambda}\right)\right]^{1-\sigma_2}}{\sum_{b'\in\mathcal{B}_g}\left[\sum_{j'\in\mathcal{J}_{gb'}} \exp\left(\frac{\delta_{j'}}{1-\lambda}\right)\right]^{1-\sigma_2}}$$
$$\times \frac{\left\{\sum_{b'\in\mathcal{B}_g}\left[\sum_{j'\in\mathcal{J}_{gb'}} \exp\left(\frac{\delta_{j'}}{1-\lambda}\right)\right]^{1-\sigma_2}\right\}^{1-\sigma_1}}{1+\sum_{g'\in\mathcal{G}}\left\{\sum_{b'\in\mathcal{B}'_g}\left[\sum_{j'\in\mathcal{J}_{g'b'}} \exp\left(\frac{\delta_{j'}}{1-\lambda}\right)\right]^{1-\sigma_2}\right\}^{1-\sigma_1}}. \tag{9}$$

Following Ben-Akiva and Lerman (1985) and Train (2009), let us define the inclusive values for each choice level as follows:

$$\text{Inclusive value for brand type } b \text{ in generation } g: \quad I_{gb} := (1-\lambda)\ln \sum_{j'\in\mathcal{J}_{gb}} \exp\left(\frac{\delta_{j'}}{1-\lambda}\right). \tag{10}$$

$$\text{Inclusive value for generation } g: \quad I_g := (1-\sigma_1)\ln \sum_{b'\in\mathcal{B}_g} \exp\left(\frac{I_{gb'}}{1-\sigma_1}\right). \tag{11}$$

I_{gb} represents the consumer's "expected utility" after generation g and brand type b have been chosen.[45] Similarly, I_g represents the consumer's "expected utility" after generation g has been chosen.[46] Using these definitions, equation (9) can be rewritten as

$$s_j = \frac{\exp\left(\frac{\delta_j}{1-\lambda}\right)}{\sum_{j'\in\mathcal{J}_{gb}} \exp\left(\frac{\delta_{j'}}{1-\lambda}\right)} \times \frac{\exp\left(\frac{I_{gb}}{1-\sigma_1}\right)}{\sum_{b'\in\mathcal{B}_g} \exp\left(\frac{I_{gb'}}{1-\sigma_1}\right)} \times \frac{\exp\left(I_g\right)}{1+\sum_{g'\in\mathcal{G}}\exp\left(I_{g'}\right)}. \tag{12}$$

This representation makes clear that the unconditional market share is a product of three logit probabilities: that of choosing product j from all products in $\mathcal{J}_{gb}$, that of choosing brand type b from all brand types in $\mathcal{B}_g$, and that of choosing generation g.

After applying the steps described in Appendix A to the components of equation (12), our estimating equation for the two-level nested logit model is derived as follows:

$$\begin{aligned}\ln(s_j) - \ln(s_0) &= \delta_j + \lambda\ln(s_{j|gb}) + \sigma_1\ln(s_{b|g}) \\ &= -\alpha p_j + \beta' x_j + \lambda\ln(s_{j|gb}) + \sigma_1\ln(s_{b|g}) + \xi_j,\end{aligned} \tag{13}$$

where s_0 is the market share of the outside good.

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[45] The consumer's maximal utility from purchasing a product belonging to brand type b in generation g, net of the error components whose values are constant within the choice set, is $\max_{j'\in\mathcal{J}_{gb}}[\delta_{j'} + (1-\lambda)\varepsilon_{gbj'}]$. Given that the maximand has a Gumbel distribution with parameters $\left(\delta_{j'},\ \frac{1}{1-\lambda}\right)$, this quantity has a distribution whose mode is $(1-\lambda)\ln\sum_{j'\in\mathcal{J}_{gb}}\exp\left(\frac{\delta_{j'}}{1-\lambda}\right)$.

[46] The consumer's maximal utility from purchasing a product belonging to generation g, net of the error component whose value is constant within the choice set, is $\max_{b'\in\mathcal{B}_g}\left\{(1-\sigma_1)\varepsilon_{gb'} + \max_{j'\in\mathcal{J}_{gb'}}[\delta_{j'} + (1-\lambda)\varepsilon_{gb'j'}]\right\}$. Given that the term in braces has a Gumbel distribution with parameters $\left(I_{gb},\ \frac{1}{1-\sigma_1}\right)$ (see footnote 43), this quantity has a distribution whose mode is $(1-\sigma_1)\ln\sum_{b'\in\mathcal{B}_g}\exp\left(\frac{I_{gb'}}{1-\sigma_1}\right)$.

B Supply

We begin by defining the set of all smartphone manufacturers by $\mathcal{M}$ and the set of all SoC manufacturers by $\mathcal{N}$. Smartphone manufacturer m's portfolio of products is assumed to be given exogenously and denoted by $\mathcal{J}_m$. The set of all smartphones is $\mathcal{J} \coloneqq \cup_{m\in\mathcal{M}}\mathcal{J}_m$, and the total number of smartphones is J. Similarly, SoC manufacturer n's portfolio of products is $\mathcal{K}_n$, the set of all SoCs is $\mathcal{K} \coloneqq \cup_{n\in\mathcal{N}}\mathcal{K}_n$, and the total number of SoCs is K. The function $m(j)$ returns the manufacturer of smartphone j, and $n(k)$ returns the manufacturer of SoC k. We define an "allocation vector" $\boldsymbol{a}$ of length J, which contains the SoC identities for each smartphone, so that if smartphone j uses SoC k, the jth element of $\boldsymbol{a}$ is $a_j = k$.

We assume that the allocation vector $\boldsymbol{a}$ is exogenously given, meaning that we do not model how transaction pairings between smartphone manufacturers and their SoC suppliers are formed.[47] Market outcomes are assumed to be determined through a static two-stage game. In the first stage, SoC manufacturers engage in a Bertrand game to set linear prices for their products (Berto Villas-Boas, 2007; Bonnet and Dubois, 2010). In the second stage, smartphone manufacturers set the retail prices for their products, taking the prices of SoCs as given and incorporating those prices into marginal costs.[48]

Smartphone Prices. In the second stage, smartphone manufacturer m's profit maximization problem can be expressed as follows, where the market subscripts have been suppressed for brevity:

$$\max_{p_j, j\in\mathcal{J}_m} \sum_{j\in\mathcal{J}_m} [(1-\phi_j)p_j - w_{a_j} - mc_j^s]Ms_j(\boldsymbol{p}). \tag{14}$$

ϕ_j is the effective per-unit royalty rate for smartphone j charged by Qualcomm, p_j is the retail price of smartphone j, w_{a_j} is the price of the SoC installed in smartphone j, mc_j^s is the marginal cost for smartphone j excluding the cost of SoC, and M is market size. $\boldsymbol{p}$ is a J-dimensional vector of all smartphone prices and $s_j(\boldsymbol{p})$ is the demand function (expressed in terms of market share) for smartphone j. We assume the following values for ϕ_j:

$$\begin{aligned}
&\text{Before 2015: } \phi_j = \begin{cases} 0 & \text{if } j \text{ complies only with GSM or TD-SCDMA} \\ 0.035 & \text{if } j \text{ complies only with LTE (or LTE and TD-SCDMA)} \\ 0.05 & \text{otherwise} \end{cases} \\
&\text{In or after 2015: } \phi_j = \begin{cases} 0 & \text{if } j \text{ complies only with GSM or TD-SCDMA} \\ 0.02275 & \text{if } j \text{ complies only with LTE (or LTE and TD-SCDMA)} \\ 0.0325 & \text{otherwise} \end{cases}
\end{aligned} \tag{15}$$

The first-order condition with respect to p_j is

$$(1-\phi_j)s_j(\boldsymbol{p}) + \sum_{h\in\mathcal{J}_{m(j)}} [(1-\phi_h)p_h - w_{a_h} - mc_h^s]\frac{\partial s_h(\boldsymbol{p})}{\partial p_j} = 0. \tag{16}$$

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[47] In ongoing work, we are modeling the process by which smartphone-SoC pairings are endogenously formed in the spirit of Eizenberg (2014).

[48] The Chinese smartphone market is different from those in the U.S. and other countries in that the handsets are usually not bundled with carrier contracts. We, therefore, follow Wang (2023) in assuming that smartphone manufacturers directly control the retail prices faced by consumers.

The first-order conditions with respect to the prices of all products can be combined into the following equation:

$$\mathrm{diag}(\mathbf{1}-\boldsymbol{\phi})\boldsymbol{s}(\boldsymbol{p})+\boldsymbol{\Omega}_s\circ\boldsymbol{\Delta}_s\left[\mathrm{diag}(\mathbf{1}-\boldsymbol{\phi})\boldsymbol{p}-\boldsymbol{A}\boldsymbol{w}-\boldsymbol{mc}^s\right]=0, \tag{17}$$

where $\boldsymbol{\phi}$ is a J-dimensional vector of royalty rates, the diag$(\cdot)$ function converts a vector into a diagonal matrix, $\boldsymbol{s}(\boldsymbol{p})$ is a vector of demands for all smartphones, and $\boldsymbol{mc}^s$ is a vector containing the non-SoC marginal costs of all smartphones. $\boldsymbol{w}$ is a K-dimensional vector containing all SoC prices, and $\boldsymbol{A}$ is an "allocation matrix" whose elements are

$$\boldsymbol{A}(j,k)=\begin{cases}1 & \text{if } a_j=k\\ 0 & \text{otherwise.}\end{cases} \tag{18}$$

$\boldsymbol{\Omega}_s$ is a J-by-J "smartphone ownership matrix" whose (j,k)th element equals 1 if $k\in\mathcal{J}_{m(j)}$ and 0 otherwise. $\boldsymbol{\Delta}_s$ is a J-by-J "smartphone response matrix" whose (j,k)th element equals $\frac{\partial s_k(\boldsymbol{p})}{\partial p_j}$, and $\circ$ represents the element-wise Hadamard product. We denote the solution to equation (17) by $\boldsymbol{p}^*(\boldsymbol{w},\boldsymbol{\phi})$.

By manipulating equation (17), we obtain the following expression for the vector of marginal costs faced by smartphone manufacturers:

$$\boldsymbol{A}\boldsymbol{w}+\boldsymbol{mc}^s=\mathrm{diag}(\mathbf{1}-\boldsymbol{\phi})\boldsymbol{p}+(\boldsymbol{\Omega}_s\circ\boldsymbol{\Delta}_s)^{-1}\left[\mathrm{diag}(\mathbf{1}-\boldsymbol{\phi})\boldsymbol{s}(\boldsymbol{p})\right] \tag{19}$$

Note that the right-hand side of equation (19) is a function of $\boldsymbol{p}$, $\boldsymbol{s}$, $\boldsymbol{\phi}$, and parameters of the demand system. Therefore, once we have the demand parameter estimates in hand, we can use equation (19) to calculate the implied vector of smartphone manufacturers' marginal costs.

SoC Prices. We assume that SoC manufacturers compete in prices to maximize profits. However, there is an important difference between Qualcomm and its rival chipmakers. Whereas Qualcomm's rivals maximize their profits from supplying SoCs, Qualcomm maximizes the sum of its SoC profits and royalty revenue from smartphone manufacturers. Using the subscript q to denote Qualcomm, the profit maximization problem of SoC manufacturer $n\neq q$ is expressed as

$$\max_{w_k,k\in\mathcal{K}_n}\sum_{k\in\mathcal{K}_n}(w_k-mc_k^c)\sum_{j\in\{j:a_j=k\}}Ms_j(\boldsymbol{p}^*(\boldsymbol{w},\boldsymbol{\phi})), \tag{20}$$

where mc_k^c is the marginal cost of SoC k and $\{j:a_j=k\}$ is the set of all smartphones that use SoC k. The first-order condition for profit maximization with respect to w_k is

$$\sum_{j\in\{j:a_j=k\}}s_j(\boldsymbol{p}^*(\boldsymbol{w},\boldsymbol{\phi}))+\sum_{h\in\mathcal{K}_{n(k)}}(w_h-mc_h^c)\sum_{j\in\{j:a_j=h\}}\sum_{l\in\mathcal{J}}\frac{\partial s_j(\boldsymbol{p}^*(\boldsymbol{w},\boldsymbol{\phi}))}{\partial p_l}\frac{\partial p_l^*(\boldsymbol{w},\boldsymbol{\phi})}{\partial w_k}=0. \tag{21}$$

Meanwhile, Qualcomm's profit maximization problem is

$$\max_{w_k,k\in\mathcal{K}_q}\sum_{k\in\mathcal{K}_q}(w_k-mc_k^c)\sum_{j\in\{j:a_j=k\}}Ms_j(\boldsymbol{p}^*(\boldsymbol{w},\boldsymbol{\phi}))+\sum_{j\in\mathcal{J}}\phi_j p_j^*(\boldsymbol{w},\boldsymbol{\phi})Ms_j(\boldsymbol{p}^*(\boldsymbol{w},\boldsymbol{\phi})), \tag{22}$$

with the second term in the objective function representing the royalty revenues received for all smartphones employing the CDMA (excluding TD-SCDMA) or LTE standard, including those that do not contain Qualcomm's chips. The first-order condition for profit maximization by Qualcomm with respect to w_k is

$$\begin{aligned}\sum_{j\in\{j:a_j=k\}} s_j(\boldsymbol{p}^*(\boldsymbol{w},\boldsymbol{\phi})) + \sum_{h\in\mathcal{K}_q}(w_h - mc_h^c)\sum_{j\in\{j:a_j=h\}}\sum_{l\in\mathcal{J}}\frac{\partial s_j(\boldsymbol{p}^*(\boldsymbol{w},\boldsymbol{\phi}))}{\partial p_l}\frac{\partial p_l^*(\boldsymbol{w},\boldsymbol{\phi})}{\partial w_k}& \\ + \sum_{j\in\mathcal{J}}\phi_j\left[\frac{\partial p_j^*(\boldsymbol{w},\boldsymbol{\phi})}{\partial w_k}s_j(\boldsymbol{p}^*(\boldsymbol{w},\boldsymbol{\phi})) + p_j^*(\boldsymbol{w},\boldsymbol{\phi})\sum_{l\in\mathcal{J}}\frac{\partial s_j(\boldsymbol{p}^*(\boldsymbol{w},\boldsymbol{\phi}))}{\partial p_l}\frac{\partial p_l^*(\boldsymbol{w},\boldsymbol{\phi})}{\partial w_k}\right] &= 0. \quad (23)\end{aligned}$$

To solve for SoC manufacturers' equilibrium price-cost margins, it is necessary to combine the first-order conditions represented by (21) and (23) into a single equation. To do so, we define two additional objects: a K-by-K "SoC ownership matrix" $\boldsymbol{\Omega}_c$, whose (j,k)th element equals 1 if $k \in \mathcal{K}_{n(j)}$ and 0 otherwise; and a "price pass-through matrix" $\boldsymbol{\Delta}_p$, whose (j,k)th element equals $\frac{\partial p_j}{\partial w_k}$. With these definitions in hand, the SoC manufacturers' first-order conditions for profit maximization can collectively be written as follows:

$$\begin{aligned}\boldsymbol{A}'\boldsymbol{s}(\boldsymbol{p}^*(\boldsymbol{w},\boldsymbol{\phi})) + \mathrm{diag}(\boldsymbol{\Omega}_c(k_q,:))\left[\boldsymbol{\Delta}_p'\mathrm{diag}(\boldsymbol{\phi})\boldsymbol{s}(\boldsymbol{p}^*(\boldsymbol{w},\boldsymbol{\phi})) + \boldsymbol{\Delta}_p'\boldsymbol{\Delta}_s\mathrm{diag}(\boldsymbol{\phi})\boldsymbol{p}^*(\boldsymbol{w},\boldsymbol{\phi})\right]& \\ + \boldsymbol{\Omega}_c \circ (\boldsymbol{\Delta}_p'\boldsymbol{\Delta}_s\boldsymbol{A})(\boldsymbol{w} - \boldsymbol{mc}^c) &= 0, \quad (24)\end{aligned}$$

where $k_q \in \mathcal{K}_q$ denotes a specific SoC supplied by Qualcomm and $\boldsymbol{\Omega}_c(k_q,:)$ is the k_qth row of $\boldsymbol{\Omega}_c$.[49] By manipulating equation (24), we obtain the following expression for the vector of SoC manufacturers' price-cost margins:

$$\begin{aligned}\boldsymbol{w} - \boldsymbol{mc}^c = &\left[\boldsymbol{\Omega}_c \circ (\boldsymbol{\Delta}_p'\boldsymbol{\Delta}_s\boldsymbol{A})\right]^{-1} \\ &\times\left\{-\boldsymbol{A}'\boldsymbol{s}(\boldsymbol{p}^*(\boldsymbol{w},\boldsymbol{\phi})) - \mathrm{diag}(\boldsymbol{\Omega}_c(k_q,:))\left[\boldsymbol{\Delta}_p'\mathrm{diag}(\boldsymbol{\phi})\boldsymbol{s}(\boldsymbol{p}^*(\boldsymbol{w},\boldsymbol{\phi})) + \boldsymbol{\Delta}_p'\boldsymbol{\Delta}_s\mathrm{diag}(\boldsymbol{\phi})\boldsymbol{p}^*(\boldsymbol{w},\boldsymbol{\phi})\right]\right\}. \quad (25)\end{aligned}$$

Following Berto Villas-Boas (2007) and Bonnet and Dubois (2010), the elements of the price pass-through matrix $\boldsymbol{\Delta}_p$ are calculated by applying the implicit function theorem to the smartphone manufacturers' first-order conditions. Denoting the left-hand side of equation (16) by $f_j(\boldsymbol{p},\boldsymbol{w})$, the kth column of $\boldsymbol{\Delta}_p$ is obtained as

$$\begin{bmatrix}\frac{\partial p_1}{\partial w_k}\\ \vdots \\ \frac{\partial p_J}{\partial w_k}\end{bmatrix} = -\begin{bmatrix}\frac{\partial f_1(\boldsymbol{p},\boldsymbol{w})}{\partial p_1} & \cdots & \frac{\partial f_1(\boldsymbol{p},\boldsymbol{w})}{\partial p_J}\\ \vdots & \ddots & \vdots \\ \frac{\partial f_J(\boldsymbol{p},\boldsymbol{w})}{\partial p_1} & \cdots & \frac{\partial f_J(\boldsymbol{p},\boldsymbol{w})}{\partial p_J}\end{bmatrix}^{-1}\begin{bmatrix}\frac{\partial f_1(\boldsymbol{p},\boldsymbol{w})}{\partial w_k}\\ \vdots \\ \frac{\partial f_J(\boldsymbol{p},\boldsymbol{w})}{\partial w_k}\end{bmatrix}. \quad (26)$$

The partial derivatives contained in the right-hand side of equation (26) are derived as follows:

$$\begin{aligned}\frac{\partial f_j(\boldsymbol{p},\boldsymbol{w})}{\partial p_h} =& (1-\phi_j)\frac{\partial s_j(\boldsymbol{p})}{\partial p_h} + \boldsymbol{\Omega}_s(j,h)(1-\phi_h)\frac{\partial s_h(\boldsymbol{p})}{\partial p_j} \\ &+ \sum_{l\in\mathcal{J}_{m(j)}}\left[(1-\phi_l)p_l - w_{a_l} - mc_l^s\right]\frac{\partial^2 s_l(\boldsymbol{p})}{\partial p_h \partial p_j}, \quad (27)\\ \frac{\partial f_j(\boldsymbol{p},\boldsymbol{w})}{\partial w_k} =& \sum_{l\in\mathcal{J}_{m(j)}}\mathbf{1}(a_l = k)\frac{\partial s_l(\boldsymbol{p})}{\partial p_j}, \quad (28)\end{aligned}$$

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[49] Note that $\boldsymbol{\Omega}_c(k,:)$ takes the same value for all $k \in \mathcal{K}_q$.

where $\mathbf{\Omega}_s(j,h)$ represents the (j,h)th element of $\mathbf{\Omega}_s$, and $\mathbf{1}(\cdot)$ is the indicator function. The first and second-order partial derivatives of market share with respect to price are derived in Appendix B for the two-level nested logit model.

5 Estimation

A Identification of Demand Parameters

To estimate equation (13), we use the following product attributes in addition to price: display size, cellular standard (GSM, cdmaOne, CDMA2000, WCDMA, TD-SCDMA, or LTE), and operating system (Android, Windows, Symbian, or other). We also use fixed effects for city and year. In addition, we use indicator variables for specific pairs of smartphone brand and SoC supplier. GSM and cdmaOne belong to second generation (2G) of cellular standards; CDMA2000, WCDMA and TD-SCDMA belong to the third generation (3G); and LTE constitutes the fourth generation (4G). Each of these generations constitutes a second-level nest (see Figure 5). The first level of nests are defined as "large" and "small" brands. We place 18 brands into the large category, and construct a dummy variable for each.[50] The iOS operating system (for iPhones) is not captured by a dummy variable, because it is perfectly collinear with the brand dummy for Apple.

We note that the product-specific error term ξ_j in equation (13) is observable to smartphone manufacturers and consumers, and may therefore affect their decisions. This implies that ξ_j may be correlated with the conditional market shares $s_{j|gb}$ and $s_{b|g}$ as well as the unobservable heterogenous preference of consumers and the price variable p_j. To deal with the potential endogeneity bias caused by this, we employ the classes of instrumental variables (IVs).

The first class of IV is, which is expected to deal with the degree of correlation in unobservable preferences for the inside goods, the number of products in each market (Björnerstedt and Verboven, 2016; Miller and Weinberg, 2017). This variable describes the competitive conditions faced by the firms in a market, so we expect it to be correlated with prices as well as conditional market shares. We assume that manufacturers' product portfolios in each market are determined before the set of $\xi_j, j \in \mathcal{J}$ are observed by firms, so that the number of products is uncorrelated with ξ_j.

We need the second class of IVs because this IV (and other IVs that treat all competing products equally) has the shortcoming that it does not account for the "closeness" between products, and hence may not accurately reflect the competitive conditions faced by firms. To address the this potential problem of weak identification, we use the second class of instrumental variables: the "differentiation IVs" initially proposed by Gandhi and Houde (2020) and further developed by Michel, Paz y Miño, and Weiergraeber (forthcoming). This class of IVs also captures competitive conditions, but has the advantage that it accounts for the closeness between products in a market.

We employ two types of differentiation IVs. The first type, which can be called "quadratic differentiation IVs", are constructed by taking the quadratic distances between products i and j in terms of continuous attributes, and summing over the j rival products to measure the competitive conditions faced by product i (Gandhi and Houde, 2020). In our application, we use the display size of smartphones as the continuous attribute. The second type, which can be called "promotion differential IVs",

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[50] The following brands are placed in the large brand category: A1, C1, G1, H1, H2, H3, H4, K1, L1, L2, M1, M2, M3, N1, O1, S1, V1, and Z1. The baseline (omitted) brand for estimation purposes is "other brands", which contains all brands belonging to the small brand category.

are constructed by summing over the promotion activities of rival products j that fall within a certain distance range (in terms of a continuous product attribute) from product i (Michel, Paz y Miño, and Weiergraeber, forthcoming). We use the natural logarithm of the sum of the number of city-markets in which product j is sold as a proxy for its promotion activities. The two types of differentiation IVs are expressed as

$$\begin{aligned} \text{Quadratic Differentiation IV:} \quad & z_{it}^{q} = \sum_{j \in \mathcal{J}} (d_{ij}^{x})^2, \\ \text{Promotion Differentiation IV:} \quad & z_{it}^{p} = \sum_{j \in \mathcal{J}} \mathbf{1}(c_{lb} < |d_{ij}^{x}| < c_{ub}) \times n_j, \end{aligned}$$

where $d_{ij}^{x} = x_i - x_j$ measures the distance between products i and j in terms of the continuous product attribute x. c_{lb} and c_{ub} are the lower bound and upper bound, respectively, of the distance range. In our application, we use the following pairs for (c_{lb}, c_{ub}): $\left(0, \frac{\max_j(d_{ij})}{3}\right)$ and $\left(\frac{\max_j(d_{ij})}{3}, \frac{2\max_j(d_{ij})}{3}\right)$. n_j is the number of city-markets where product j is sold.

Finally, we use the cost-shifter variables as the third class of IVs to deal with the correlation between structural error ξ_i and prices(Miller and Weinberg (2017)).

We estimate equation (13), subject to instrumental variables, using the generalized method of moments (GMM).

B Estimation Results

Tables 2 and 3 display our estimates for the two-level nested logit demand system. Starting with Table 2, the price coefficient α is -0.001 and statistically significant at the 1 percent level. The parameter λ, which represents the degree to which consumers' unobserved utility is correlated across products within the same brand type for a given generation, is 0.398 and statistically significant. The parameter σ_1, representing the degree to which unobserved utility is correlated within the same generation, is also statistically significant at 0.094. As expected, the estimate for σ_1 is smaller than that for λ.

Turning to the product attributes, we find that larger display size yields higher utility. We also find that 3G standards (CDMA2000, WCDMA, and TD-SCDMA) generate higher utility than 2G standards (GSM and cdmaOne), and that LTE generates even greater utility. Consumers are found to prefer the Android operating standard over Windows, while the Symbian operating system is found to generate higher utility than Android. As shown in Table 3, Apple smartphones (which exclusively use the iOS operating system) generate greater utility than the baseline category, which is defined as "small smartphone brands using the Android operating system and containing SoCs from suppliers other than Qualcomm, H, M, and SP". We cannot separately identify the brand effect of Apple and the operating system effect of iOS.

The other coefficient estimates in Table 3 show that consumers receive higher utility from smartphone products supplied by large brands, relative to smaller brands in the "other brands" category. For the smartphone brands marked with a hash symbol (C1, H1, H2, O1, and V1), consumers receive similar utility from products containing Qualcomm SoCs and those containing SoCs from M. This suggests that for these brands, Qualcomm is in close competition with M.

Table 2: Demand Estimates (1): Overall

	Coefficient	S.E.
price: α	-0.001^{***}	(0.000)
$\ln(s_{j\|bg})$: λ	0.398^{***}	(0.026)
$\ln(s_{b\|g})$: σ_1	0.094^{**}	(0.043)
Display size(inch)	0.635^{***}	(0.031)
Cellular standard (GSM = 0)		
cdmaOne	0.101^{***}	(0.016)
CDMA2000	0.920^{***}	(0.047)
WCDMA	0.967^{***}	(0.056)
TD-SCDMA	0.958^{***}	(0.052)
LTE	1.486^{***}	(0.096)
Operating System (Android = 0)		
OS:Windows	-0.442^{***}	(0.034)
OS:Symbian	0.462^{***}	(0.065)
OS:Other	-0.076	(0.050)
Smartphone brand dummies × processor brand dummies (See Table 3)		
Year dummies	Yes	
City dummies	Yes	
Constant	-9.949^{***}	(0.234)
N	270,301	
R^2	0.586	
$Hansen's\ J$	chi2(1) = 7.571	$p = 0.006$

Note 1: Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Note 2: Dummy for iOS of Apple is dropped as it is identical to Apple brand dummy.

Table 3: Demand Estimates (2): Coefficients of Smartphone Brand × SoC Supplier Dummies

SoC supplier	Qualcomm		M		H		P		Other suppliers	
	Coef.	S.E.	Coef.	S.E.	Coef.	S.E.	Coef.	S.E.	Coef.	S.E.
Smartphone brand										
A1									6.177	(.232)
C1	1.567#	(.026)	1.597#	(.038)			2.116	(.037)	1.368	(.035)
G1	1.617	(.054)	2.167	(.029)			1.932	(.097)	1.810	(.083)
H1	1.809#	(.021)	1.815#	(.033)	3.538	(.088)	1.639	(.074)	1.438	(.058)
H2	1.964#	(.038)	1.815#	(.052)	2.255	(.028)				
H3	2.855	(.068)	1.461	(.243)					3.010	(.102)
H4	0.916	(.059)	0.675	(.082)			1.463	(.098)	0.474	(.095)
K1	0.936#	(.054)	1.110#	(.082)			1.380	(.063)	1.192	(.059)
L1	1.438	(.032)	1.815	(.022)			2.071	(.061)	1.631	(.053)
L2	1.224	(.092)	1.644	(.023)						
M1	2.107	(.025)	1.800	(.048)					2.989	(.104)
M2	1.972	(.066)	1.589	(.037)					2.183	(.065)
M3	2.040	(.052)	1.740	(.223)					2.621	(.081)
N1	3.579	(.094)	1.740	(.223)					2.032	(.063)
O1	3.063#	(.056)	3.094#	(.060)					2.306	(.191)
S1	3.181	(.078)	2.343	(.103)			2.568	(.075)	3.181	(.104)
V1	2.925#	(.047)	2.829#	(.051)						
Z1	1.042#	(.044)	1.161#	(.046)			1.628	(.089)	1.038	(.058)
Other brands	−0.017	(.015)	−0.070	(.013)			0.030	(.024)	–	

Note 1: Standard errors in parentheses.

Note 2: All coefficient estimates are statistically significant with p values lower than 0.01, except terms *Other brands* × *Qualcomm* (p = 0.286) and *Other brands* × SP (p = p.220)

Note 3: The smartphone brands marked with # are those for which the coefficient on the brand-supplier dummy for Qualcomm is similar to that on the brand-supplier dummy for M (in the sense that the difference between the two is less than 0.15).

Table 4: Estimated Own Price Elasticities

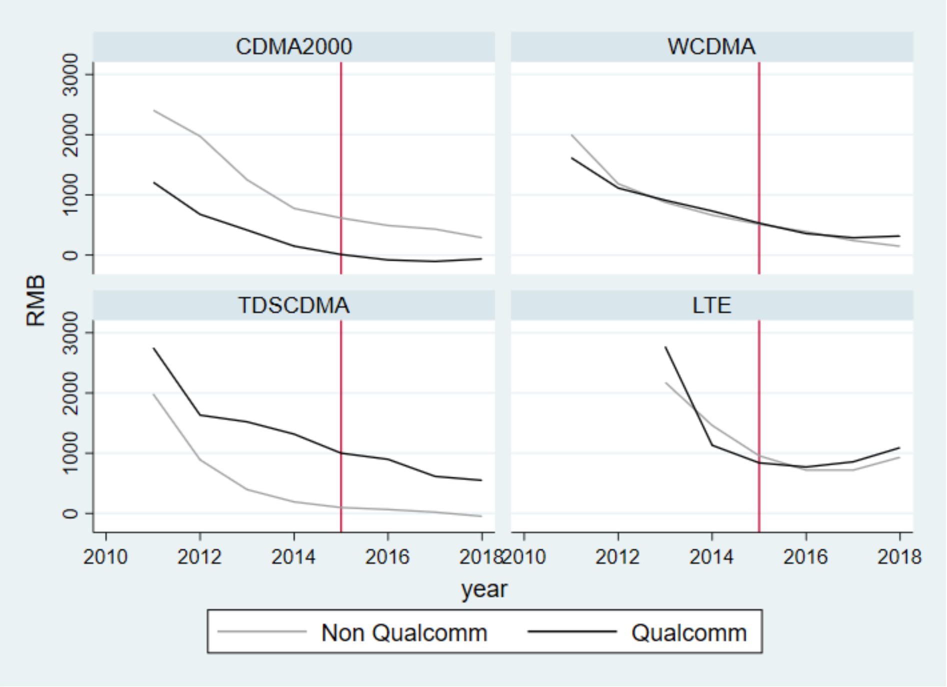
	Mean	S.D.	Min	Max
Smartphone brand				
A1	−8.2	3.2	−21.5	−0.10
H1+H2	−2.8	2.3	−31.9	−0.24
M1	−2.4	1.3	−10.0	−0.41
M2	−2.2	1.1	−7.1	−0.17
O1 + V1	−3.2	1.5	−17.1	−0.72
S1	−4.3	4.2	−43.8	−0.35

Table 4 summarizes the estimated own-price elasticities of demand for selected smartphone brands. The mean and standard deviation are taken over products and markets. The mean own-price elasiticity varies between -8.2 for A1 and -2.2 for M2.

C Smartphone Marginal Costs

Using our demand estimates, we are able to calculate the implied marginal costs of smartphones, inclusive of SoC prices, using equation (19). Figure 6 plots the mean of the implied marginal costs, taken separately by cellular standard and SoC source (Qualcomm or non-Qualcomm). For the three standards in which Qualcomm has a large patent portfolio and charges royalties – CDMA2000, WCDMA, and LTE – there appears to be a slight uptick in marginal costs after 2015 for smartphones containing Qualcomm chips, against a trend of lowering marginal costs.

Figure 6: Implied Marginal Costs for Smartphone Manufacturers



6 Counterfactual Analysis

A Estimating the Impact of the NDRC Intervention

The antitrust branch of the Chinese government (NDRC) found in February 2015 that Qualcomm's licensing practices for its SEPs covering the cdmaOne, CDMA2000, WCDMA, and LTE standards violated the country's Anti-Monopoly Law. As part of the remedies, Qualcomm was ordered to effectively reduce the royalty rates it charges on smartphone sales. This is reflected in equation (15), which shows that the effective royalty rates on smartphones compliant with the cdmaOne, CDMA2000, and WCDMA standards were reduced from 5 percent to 3.25 percent, while those on smartphones compliant only with the LTE standard (or only with the LTE and TD-SCDMA standards) were reduced from 3.5 percent to 2.275 percent.

In our counterfactual analysis, we envision a hypothetical scenario where the NDRC did not intervene in this manner. Thus, we allow Qualcomm's royalty rates to remain at pre-2015 levels (5 percent for smartphones compliant with cdmaOne, CDMA2000, and WCDMA; 3.5 percent for smartphones compliant only with LTE, or only with LTE and TD-SCDMA) for the years 2015 and beyond. We calculate the counterfactual equilibrium, for each city in 2018, by finding the vector of price-cost margins for SoC suppliers such that the first-order conditions in equation (25) are satisfied under the hypothetical scenario. This is shown in equation (29), where ϕ^{cf} denotes Qualcomm's royalty rates under the hypothetical scenario, and $\Delta \boldsymbol{w}$ is the change in SoC prices required to satisfy SoC suppliers' first-order conditions for profit maximization.

$$\begin{aligned}
\boldsymbol{w} + \Delta \boldsymbol{w} - \boldsymbol{mc}^c = {} & \left[\boldsymbol{\Omega}_c \circ (\boldsymbol{\Delta}_p' \boldsymbol{\Delta}_s \boldsymbol{A})\right]^{-1} \\
& \times \Big\{ - \boldsymbol{A}' \boldsymbol{s} \left(\boldsymbol{p}^* \left(\boldsymbol{w} + \Delta \boldsymbol{w}, \boldsymbol{\phi}^{cf}\right)\right) - \operatorname{diag}(\boldsymbol{\Omega}_c(k_q, :)) \\
& \times \left[\boldsymbol{\Delta}_p' \operatorname{diag}\left(\boldsymbol{\phi}^{cf}\right) \boldsymbol{s} \left(\boldsymbol{p}^* \left(\boldsymbol{w} + \Delta \boldsymbol{w}, \boldsymbol{\phi}^{cf}\right)\right) + \boldsymbol{\Delta}_p' \boldsymbol{\Delta}_s \operatorname{diag}\left(\boldsymbol{\phi}^{cf}\right) \boldsymbol{p}^* \left(\boldsymbol{w} + \Delta \boldsymbol{w}, \boldsymbol{\phi}^{cf}\right)\right] \Big\}
\end{aligned} \tag{29}$$

While our model allows us to identify SoC suppliers' price-cost margins, data limitations preclude the separate identification of SoC prices and suppliers' marginal costs. Under the assumption that SoC suppliers' marginal costs are constant, however, we can identify the required change in SoC prices $\Delta \boldsymbol{w}$, because it is equivalent to the required change in SoC suppliers' price-cost margins. Thus, our estimate for the NDRC intervention's effect on SoC prices is given by $-\Delta \boldsymbol{w}$, and its effect on smartphone manufacturers' marginal costs is given by $-\boldsymbol{A} \Delta \boldsymbol{w}$ (recall that $\boldsymbol{A}$ maps SoCs to smartphones).

Using these results, we can calculate the change in smartphone prices caused by the NDRC intervention as $\boldsymbol{p}^*(\boldsymbol{w}, \boldsymbol{\phi}) - \boldsymbol{p}^* \left(\boldsymbol{w} + \Delta \boldsymbol{w}, \boldsymbol{\phi}^{cf}\right)$, where $\boldsymbol{p}^* \left(\boldsymbol{w} + \Delta \boldsymbol{w}, \boldsymbol{\phi}^{cf}\right)$ is the solution to the first-order conditions for smartphone manufacturers' profit maximization under the counterfactual, given by:

$$\operatorname{diag}(\boldsymbol{1} - \boldsymbol{\phi}) \boldsymbol{s}(\boldsymbol{p}) + \boldsymbol{\Omega}_s \circ \boldsymbol{\Delta}_s \left[\operatorname{diag}\left(\boldsymbol{1} - \boldsymbol{\phi^{cf}}\right) \boldsymbol{p} - \boldsymbol{A}(\boldsymbol{w} + \Delta \boldsymbol{w}) - \boldsymbol{mc}^s\right] = 0. \tag{30}$$

When solving (30) for $\boldsymbol{p}$, we estimate smartphone manufacturers' marginal costs under the counterfactual, $\boldsymbol{A}(\boldsymbol{w} + \Delta \boldsymbol{w}) + \boldsymbol{mc}^s$, by adding $\boldsymbol{A} \Delta \boldsymbol{w}$ to our original marginal cost estimates obtained from equation (19).

Employing the shorthand $\boldsymbol{p}^o = \boldsymbol{p}^*(\boldsymbol{w}, \boldsymbol{\phi})$ and $\boldsymbol{p}^{cf} = \boldsymbol{p}^* \left(\boldsymbol{w} + \Delta \boldsymbol{w}, \boldsymbol{\phi}^{cf}\right)$ and following Small and Rosen (1981), we can calculate the change in expected consumer surplus resulting from the NDRC intervention as

$$\Delta E(CS) = \frac{M}{\alpha}\left[\ln\left(1+\sum_{g'\in\mathcal{G}}\left\{\sum_{b'\in\mathcal{B}_{g'}}\left[\sum_{j'\in\mathcal{J}_{g'b'}}\exp\left(\frac{\delta^{o}_{j'}}{1-\lambda}\right)\right]^{1-\sigma_2}\right\}^{1-\sigma_1}\right) - \ln\left(1+\sum_{g'\in\mathcal{G}}\left\{\sum_{b'\in\mathcal{B}_{g'}}\left[\sum_{j'\in\mathcal{J}_{g'b'}}\exp\left(\frac{\delta^{cf}_{j'}}{1-\lambda}\right)\right]^{1-\sigma_2}\right\}^{1-\sigma_1}\right)\right], \tag{31}$$

where $\delta^{o}_{j'}$ and $\delta^{cf}_{j'}$ represent consumers' mean utility under the actual scenario (with intervention) and counterfactual scenario (without intervention), respectively.

B Results

Intervention Impact in a Representative Market. The histograms in panels (a) through (c) of Figure 7 show the NDRC intervention's effect on the costs, prices, and quantities of smartphone products sold in Beijing in 2018. Panel (a) reveals that, while the impact on smartphone marginal costs varied across products, it was almost always positive. This conforms with our theoretical prediction from Section 2D that an exogenous reduction in royalty rates causes an increase in SoC prices. The same effect is evident in panel (d), which shows that the intervention had a largely positive impact on SoC suppliers' price-cost margins.

Meanwhile, panel (b) shows that the intervention's impact on smartphone prices was mostly negative. This implies that the price-lowering effect of the royalty reduction – via a reduction in smartphone manufacturers' perceived marginal costs – tended to overwhelm the increase in SoC prices caused by the intervention. As a result, for a large number of smartphone products, sales volume increased as a result of the intervention, as evidenced in panel (c). These results are mirrored in the other cities covered by our dataset.[51]

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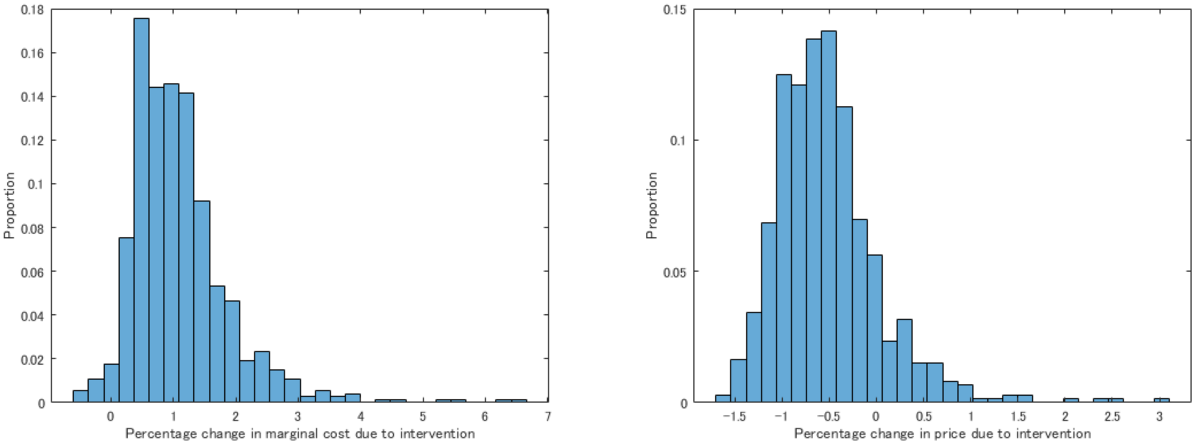
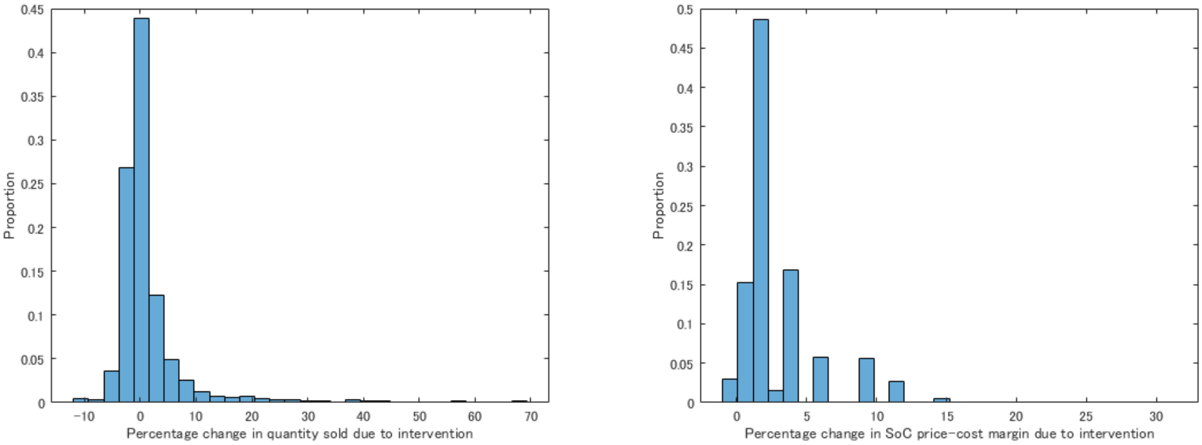
[51] Histograms for the other cities are available from the authors upon request.

Figure 7: Changes Due to NDRC Intervention: Beijing, 2018



(a) Smartphone marginal costs

(b) Smartphone prices



(c) Smartphone units sold

(d) SoC price-cost margins

Source: Authors' estimation.
Note: The histograms in panels (a) through (c) show the distribution of smartphone products, while the histogram in panel (d) shows the distribution of SoC products.

Table 5: Welfare Effects of NDRC Intervention: Changes by City in 2018

City	(1) Smartphone marginal cost (weighted average, %)	(2) Smartphone price (weighted average, %)	(3) Consumer surplus per smartphone (RMB)	(4) Overall consumer surplus (million RMB)	(5) SoC profit (million RMB)	(6) Smartphone profit (million RMB)	(7) Qualcomm's royalty revenue (million RMB)	(8) Total surplus (million RMB)
Beijing	0.871	−0.720	23.7	213	275	218	−360	376
Changsha	1.182	−0.514	15.1	24	41	30	−53	43
Chengdu	0.964	−0.662	20.4	73	108	84	−133	133
Chongqing	1.176	−0.504	14.5	43	80	60	−95	88
Guangzhou	1.096	−0.545	15.4	66	103	83	−134	119
Harbin	1.050	−0.609	19.3	42	63	50	−75	80
Hefei	1.158	−0.521	14.5	25	41	30	−53	42
Kunming	1.211	−0.447	11.8	32	64	47	−81	60
Nanjing	0.878	−0.736	25.6	74	97	74	−124	121
Nanning	1.309	−0.376	9.7	16	36	28	−42	37
Ningbo	1.130	−0.548	16.4	22	37	27	−47	39
Shanghai	0.901	−0.702	22.7	196	258	204	−338	320
Shenyang	1.206	−0.493	14.6	29	50	37	−66	51
Shijiazhuang	1.153	−0.536	16.1	20	33	25	−42	37
Suzhou	0.948	−0.678	21.6	45	62	48	−80	75
Tianjin	1.058	−0.597	17.5	70	107	82	−138	122
Xiamen	1.152	−0.519	14.5	18	31	22	−42	30
Xian	1.136	−0.520	14.8	36	61	47	−79	66
18 cities' total	1.085	−0.570	16.8	1047	1551	1204	−1991	1811

Note: Changes in smartphone marginal cost (column 1) and smartphone price (column 2) are presented as quantity-weighted averages over products.
Total surplus (column 8) is calculated as the sum of columns 4 to 7.

Effect on Welfare Measures. Table 5 summarizes our simulation results by city. Column 1 shows that the weighted average change in smartphone marginal costs was positive in every city, ranging from 0.871 to 1.206 percent. This confirms our theoretical prediction in Section 2D that an exogenous reduction in the royalty rate increases the price of SoCs. Meanwhile, column 2 reveals that the weighted average change in smartphone prices was negative in every city. While the magnitude of price reduction was small, ranging between −0.376 and −0.736 percent (which is understandable given that the change in royalties is small relative to smartphone prices), the consistently negative sign supports the NDRC's central theory of harm that Qualcomm's elevated royalty rates caused smartphone prices to increase.

Consumer surplus increased in every city as a result of the NDRC intervention, as is evident from column 4. As shown in column 3, the magnitude of the consumer surplus increase, measured in per-smartphone unit terms, varies from RMB 9.7 to 25.6 ($1.47 to 3.87 at the prevailing exchange rate) per year. This amounts to 0.35 to 0.92 percent of the quantity-weighted average price of smartphones in 2018 (RMB 2,793) – a small but non-negligible increase.

With regard to the impact on firm profits, the effect on SoC suppliers' profit (disregarding the effect on Qualcomm's royalty revenues for now) was positive. Column 5 shows that the combined profits from SoC supply (including Qualcomm's) increased in every city. This is unsurprising, given that most SoCs experienced a price increase, and the general decrease in smartphone prices meant that the sales volume of SoCs tended to increase. The increase in SoC profits was greater than the increase in consumer surplus, ranging from 129 percent of the consumer surplus increase in Beijing, to 219 percent of the consumer surplus increase in Nanning.

The overall effect on smartphone manufacturers' profits was also positive in every city (column 6), although it was smaller than the effect on SoC suppliers' profits. The intervention allowed smartphone manufacturers to earn higher profits, despite having to pay higher SoC prices and charging lower prices for their smartphones, because their royalty payments to Qualcomm decreased substantially. This is seen in column 7, which shows that the reduction in Qualcomm's royalty revenue was quite large. By summing up the results in columns 4 through 7, we obtain city-wise estimates for the NDRC intervention's effect on total surplus (column 8). It is positive in every city, ranging from RMB 30 million per year in Xiamen to RMB 376 million per year in Beijing.

Heterogeneous Impact on Smartphone Manufacturers and SoC Suppliers. The NDRC intervention had a heterogenous effect on smartphone manufacturers depending on their source of SoCs. As shown in panel (a) of Figure 8, smartphone products containing Qualcomm SoCs tended to experience a larger increase in marginal cost (due to higher SoC prices), relative to those containing non-Qualcomm SoCs, and as a result their prices were more likely to increase (panel (b)). As a consequence, smartphones containing Qualcomm chips were more likely to experience a reduction in profit, relative to smartphones containing non-Qualcomm chips (panel (c)). These results suggest that Qualcomm had a greater incentive than other chipmakers to increase the price of SoCs after the intervention. While the reduction in royalty rates incentivized all SoC suppliers to increase their prices in the face of increased derived demand from smartphone manufacturers, it appears that Qualcomm's optimal response was to raise its SoC prices even further, possibly to stem the fall in royalty revenue.[52]

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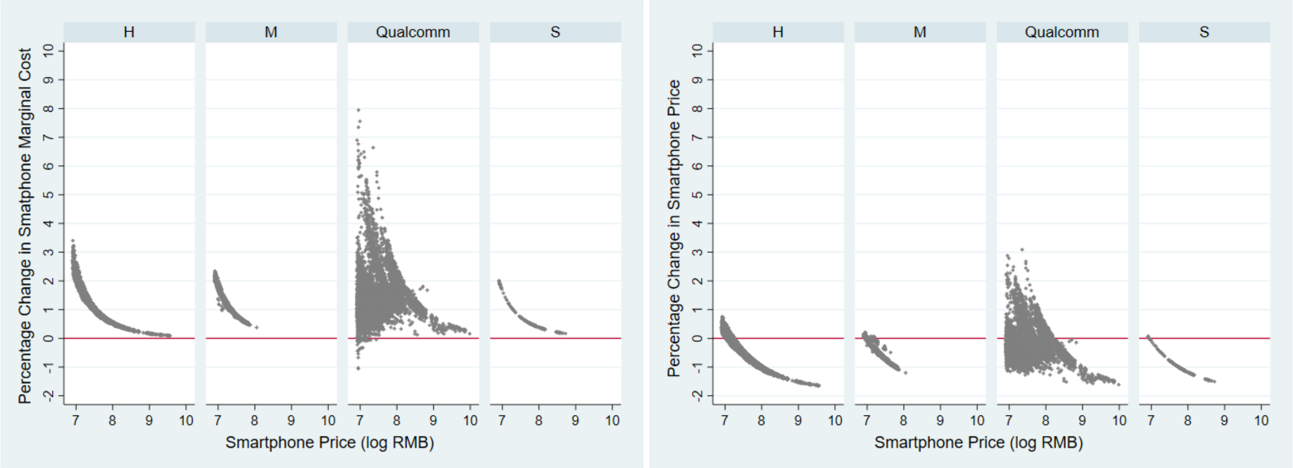
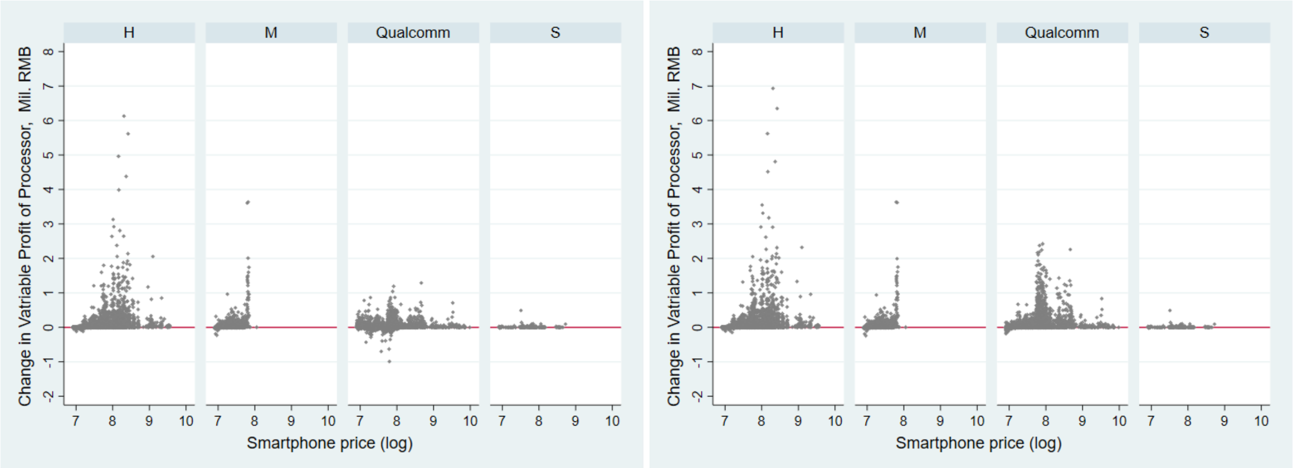
[52] All SoC suppliers, including Qualcomm, are incentivized to increase their prices in response to a price increase by

Figure 8: Effect of NDRC Intervention on Smartphones: By SoC Source



(a) Smartphone marginal costs

(b) Smartphone prices



(c) Smartphone profits

(d) SoC profits

Note: Each dot represents a smartphone product, with simple averages taken over the 18 cities shown in Table 5.

The higher SoC prices after the intervention, coupled with the tendency of SoC sales volume to increase (as a result of lower smartphone prices), increased the profits from SoC supply. Panel (d) of Figure 8 as well as Table 6 illustrate this effect for individual SoC suppliers. H was the largest gainer; its variable profit (defined as revenue minus variable cost) increased by 4.9 percent as a result of the intervention. Qualcomm's variable profit increased as well, but this was overwhelmed by the reduction in royalty revenue (which amounted to RMB 1.99 billion in 2018), causing the sum of Qualcomm's variable profit from SoC supply and royalty revenue to decrease by 6.8 percent.

The SoC suppliers' heterogeneous response to the intervention translates into a differential impact among smartphone manufacturers. As shown in panel (a) of Figure 9, smartphone brands H1 and H2 (which are owned by the same company) tended to experience a relatively small percentage increase in marginal cost after the NDRC intervention, while brand M1 tended to experience a large increase. This can be attributed to a difference in their SoC sourcing strategies. The owner of H1 and H2 has an SoC subsidiary, called H, from which the two brands source much of their SoC requirements.[53] This

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rivals; this strategic complementarity is a hallmark of price competition models.

[53] In 2018, 72.1 percent of H1's products and 84.2 percent of H2's products in the 4G category used SoCs supplied by

Table 6: Impact of NDRC Intervention on SoC Suppliers' Profits in 2018

SoC Supplier	H	M	Qualcomm	S
		Change in mil. RMB		
Profit from SoC supply	391.5	82.4	367.8	2.6
Royalty revenue	-	-	-1991.5	-
		Percentage change		
Variable profit from SoC supply	4.9	2.4	3.7	3.5
Variable profit and royalty revenue	-	-	-6.8	-

Note: Based on 12,502 observations in 18 cities.

Table 7: Impact of NDRC Intervention on Smartphone Manufacturers' Profits in 2018

Smartphone manufacturer	H1+H2	M1	M2	O1+V1	S1
			Change in mil. RMB		
Profit from smartphone supply	359.8	-11.3	5.2	197.2	30.8
Royalty payment	-579.9	-81.1	-19.7	-654.6	-67.8
			Percentage change		
Smartphone marginal cost	0.7	2.4	1.4	1.3	1.1
Smartphone price	-0.8	0.4	-0.2	-0.3	-0.7
Smartphone units sold	2.6	-2.0	-0.7	0.3	5.4
Variable profit	4.5	-0.9	1.6	2.0	5.9
Royalty payment	-32.8	-36.6	-35.3	-35.0	-31.3

Note: The percentage change in smartphone marginal costs and prices are quantity-weighted averages.

has allowed H1 and H2 to limit their dependence on Qualcomm products.[54] To a large extent, H1 and H2 were able to shield themselves from the drastic increase in SoC price by Qualcomm, so that most of their smartphone products experienced a price reduction in response to the intervention, as seen in panel (b) of Figure 9. As a result, H1 and H2 were able to increase their profits, as is apparent from panel (c) of Figure 9. From the first column of Table 7, we can see that H1 and H2's profit increase was driven by the large reduction in royalty payments to Qualcomm; H1 and H2's royalty payments decreased by 32.8 percent as a result of the intervention, and other smartphone brands' payments experienced a similar reduction.

By contrast, brand M1 has sourced a large share of its SoC requirements from Qualcomm.[55] This has resulted in M1's products experiencing a large post-intervention increase in marginal cost (panel (a) of Figure 9), and a relatively large proportion of those products experienced a price increase (panel (b)). As a consequence, M1's profits fell following the NDRC intervention, and this can be seen in Table 7 as well as panel (c) of Figure 9.

Overall, the NDRC intervention's impact on smartphone manufacturers appears to have varied according to the following factors: (i) whether or not the smartphone manufacturer is vertically

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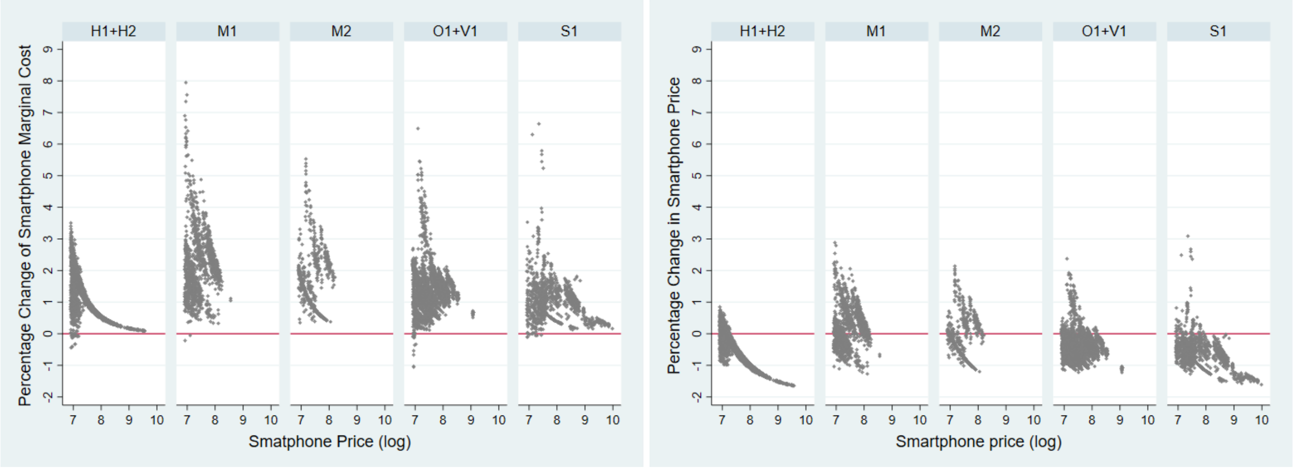
H.

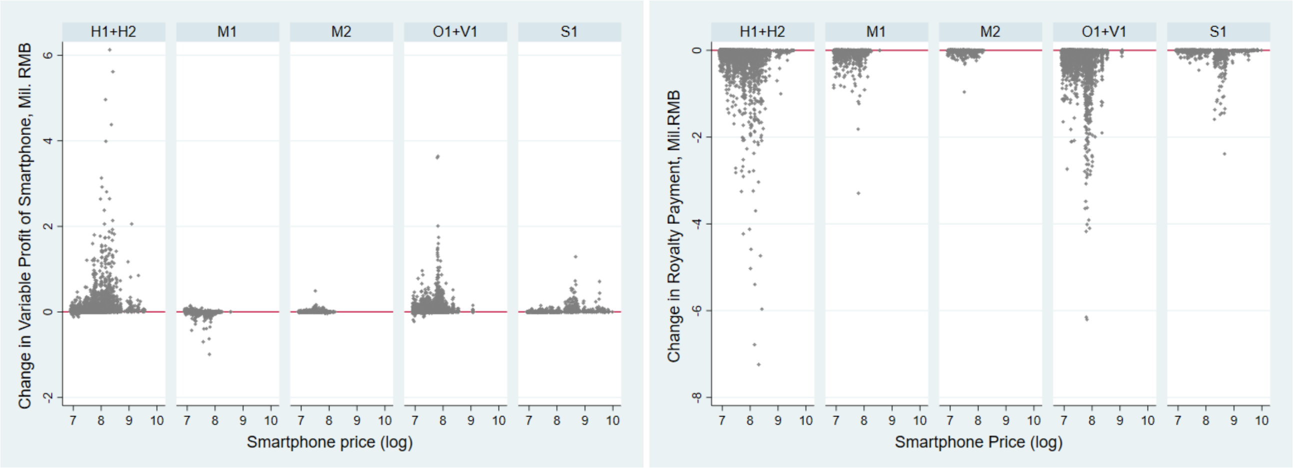
[54] To illustrate, only 22.6 percent of H1's products and 13.9 percent of H2's products in the 4G category used SoCs supplied by Qualcomm in 2018.

[55] In 2018, 87.4 percent of M1's products in the 4G category used Qualcomm SoCs.

Figure 9: Effect of NDRC Intervention on Smartphones: By Smartphone Brand



(a) Smartphone marginal costs (b) Smartphone prices



(c) Smartphone profits (d) Royalty payments to Qualcomm

Note: Each dot represents a smartphone product, with simple averages taken over the 18 cities shown in Table 5. Brands H1 and H2, and brands O1 and V1 are respectively two brands owned by the same company.

integrated into SoC supply (as in the case of H1 and H2), and (ii) the price range of the smartphone manufacturer's product portfolio. With regard to the latter factor, S1 was able to lower the price for most of its products and increase its profit, even though its reliance on Qualcomm chips was fairly high (panels (b) and (c) of Figure 9).[56] This is because S1's product portfolio contains a relatively large number of high-priced smartphones, implying that the percentage increase in smartphone marginal costs was kept low (panel (a)).[57]

7 Conclusion

The effect of Qualcomm's licensing policy for its standard-essential patents (SEPs) on market outcomes has been the subject of intense debate and legal dispute. In particular, it has been an open question whether the elevated royalty rates charged by Qualcomm had the effect of increasing smartphone

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[56] In 2018, 87.7 percent of S1's products in the 4G category used Qualcomm SoCs.

[57] Further details regarding the heterogeneous impact of the intervention on SoC suppliers and smartphone manufacturers are available from the authors upon request.

prices, to the detriment of consumers. Our theoretical analysis revealed that elevated royalty rates could lead to either higher or lower smartphone prices, so that the actual effect in a specific market is an empirical question.

The 2015 intervention by China's antitrust agency, the NDRC, lowered the effective royalty rate that Qualcomm charges to smartphone manufacturers by 1.23 - 1.75 percentage points. We evaluated the effect of this policy through a counterfactual analysis based on a structural econometric model covering the vertically related markets for smartphones and SoCs. Using our estimates for the model, we calculated SoC suppliers' price-cost margins and smartphone prices for each city in 2018, under the counterfactual scenario that the NDRC did not intervene. By comparing these results with the actual outcomes, we found that the intervention increased smartphone manufacturers' marginal costs by around 1.1 percent on average, and that it lowered smartphone prices by around 0.6 percent on average.

As a result, consumer surplus increased by around RMB 1 billion in 2018 in the 18 cities covered by our analysis. SoC suppliers' profits (excluding Qualcomm's royalty receipts) increased by around RMB 1.6 billion, but the increase in Qualcomm's SoC profits was overwhelmed by the reduction in its royalty revenue (around 2.0 billion). Smartphone manufacturers' profits increased by around RMB 1.2 billion, but some manufacturers experienced a reduction in profit. Total surplus increased by around RMB 1.8 billion, so that in hindsight, the intervention can be justified on static social welfare grounds.

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Appendix A Derivation of Estimating Equation for the Two-Level Nested Logit Demand Model

Using the definition of the inclusive value for brand type b, the choice probability of product j, conditional on brand type b in generation g being chosen, can be rewritten as $s_{j|gb} = \frac{\exp\left(\frac{\delta_j}{1-\lambda}\right)}{\exp\left(\frac{I_{gb}}{1-\lambda}\right)}$. Taking its natural logarithm and rearranging yields

$$\ln(s_{j|gb}) = \delta_j + \lambda \ln(s_{j|gb}) - I_{gb}.$$

Similarly using the definition of the inclusive value for generation g, the choice probability of brand type b, conditional on generation g being chosen, can be rewritten as $s_{b|g} = \frac{\exp\left(\frac{I_{gb}}{1-\sigma_1}\right)}{\exp\left(\frac{I_g}{1-\sigma_1}\right)}$. Taking its natural logarithm and rearranging yields

$$\ln(s_{b|g}) = \sigma_1 \ln(s_{b|g}) + I_{gb} - I_g.$$

We also note that $\ln(s_g) = I_g - \ln[1 + \sum_{g' \in \mathcal{G}} \exp(I_{g'})]$ and

$$\ln(s_0) = \ln\left[\frac{1}{1 + \sum_{g' \in \mathcal{G}} \exp(I_{g'})}\right] = -\ln[1 + \sum_{g' \in \mathcal{G}} \exp(I_{g'})].$$

Combining these results, we obtain the estimation equation in (13):

$$\begin{aligned}\ln(s_j) - \ln(s_0) &= \ln(s_{j|gb}) + \ln(s_{b|g}) + \ln(s_g) - \ln(s_0)\\ &= \delta_j + \lambda \ln(s_{j|gb}) + \sigma_1 \ln(s_{b|g}).\end{aligned}$$

Appendix B Partial Derivatives of Unconditional Market Share

First-order partial derivatives.

$$\frac{\partial s_j}{\partial p_k} = \begin{cases} -\frac{\alpha s_j}{1-\lambda}\left[1-\sigma_2 s_{j|gb}-\sigma_1(1-\sigma_2)s_{j|gb}s_{b|g}-(1-\lambda)s_j\right] \\ \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{if } k=j \\ \frac{\alpha s_j}{1-\lambda}\left[\sigma_2 s_{k|gb}+\sigma_1(1-\sigma_2)s_{k|gb}s_{b|g}+(1-\lambda)s_k\right] \\ \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{if } k\in\mathcal{J}_{gb}, k\neq j \\ \frac{\alpha s_j}{1-\lambda}\left[\sigma_1(1-\sigma_2)s_{k|gb'}s_{b'|g}+(1-\lambda)s_k\right] \\ \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{if } k\in\mathcal{J}_{gb'} \\ \alpha s_j s_k \\ \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{if } k\in\mathcal{J}_{g'} \end{cases}$$

$$\frac{\partial s_{j|gb}}{\partial p_k} = \begin{cases} -\frac{\alpha}{1-\lambda}s_{j|gb}(1-s_{j|gb}) & \text{if } k=j \\ \frac{\alpha}{1-\lambda}s_{j|gb}s_{k|gb} & \text{if } k\in\mathcal{J}_{gb}, k\neq j \\ 0 & \text{if } k\notin\mathcal{J}_{gb} \end{cases}$$

$$\frac{\partial s_{b|g}}{\partial p_k} = \begin{cases} -\frac{\alpha(1-\sigma_2)}{1-\lambda}s_{k|gb}s_{b|g}(1-s_{b|g}) & \text{if } k\in\mathcal{J}_{gb} \\ \frac{\alpha(1-\sigma_2)}{1-\lambda}s_{k|gb'}s_{b'|g}s_{b|g} & \text{if } k\in\mathcal{J}_{gb'} \\ 0 & \text{if } k\in\mathcal{J}_{g'} \end{cases}$$

Second-order partial derivatives.

$$
\frac{\partial^2 s_j}{\partial p_l \partial p_k} =
\begin{cases}
\begin{aligned}
&\frac{\alpha^2 s_j}{(1-\lambda)^2} \Big\{ \big[1 - \sigma_2 s_{j|gb} - \sigma_1(1-\sigma_2) s_{j|gb} s_{b|g} - (1-\lambda) s_j\big] \\
&\quad \times \big[1 - \sigma_2 s_{j|gb} - \sigma_1(1-\sigma_2) s_{j|gb} s_{b|g} - 2(1-\lambda) s_j\big] \\
&\qquad - \big[\sigma_2 + \sigma_1(1-\sigma_2) s_{b|g}\big] s_{j|gb}(1 - s_{j|gb}) \\
&\qquad\quad - \sigma_1(1-\sigma_2)^2 s_{j|gb}^2 s_{b|g}(1 - s_{b|g}) \Big\}
\end{aligned} & \text{if } k = l = j \\[2ex]
\begin{aligned}
&- \frac{\alpha^2 s_j}{(1-\lambda)^2} \Big\{ \big[1 - \sigma_2 s_{j|gb} - \sigma_1(1-\sigma_2) s_{j|gb} s_{b|g} - 2(1-\lambda) s_j\big] \\
&\quad \times \big[\sigma_2 s_{l|gb} + \sigma_1(1-\sigma_2) s_{l|gb} s_{b|g} + (1-\lambda) s_l\big] \\
&\qquad - \big[\sigma_2 + \sigma_1(1-\sigma_2) s_{b|g}\big] s_{j|gb} s_{l|gb} \\
&\qquad\quad + \sigma_1(1-\sigma_2)^2 s_{j|gb} s_{b|g} s_{l|gb}(1 - s_{b|g}) \Big\}
\end{aligned} & \text{if } k = j, l \in \{\mathcal{J}_{gb} \setminus j\} \\[2ex]
\begin{aligned}
&- \frac{\alpha^2 s_j}{(1-\lambda)^2} \Big\{ \big[1 - \sigma_2 s_{j|gb} - \sigma_1(1-\sigma_2) s_{j|gb} s_{b|g} - 2(1-\lambda) s_j\big] \\
&\quad \times \big[\sigma_1(1-\sigma_2) s_{l|gb'} s_{b'|g} + (1-\lambda) s_l\big] \\
&\qquad - \sigma_1(1-\sigma_2)^2 s_{j|gb} s_{b|g} s_{l|gb'} s_{b'|g} \Big\}
\end{aligned} & \text{if } k = j, l \in \mathcal{J}_{gb'} \\[2ex]
- \frac{\alpha^2 s_j s_l}{1-\lambda} \big[1 - \sigma_2 s_{j|gb} - \sigma_1(1-\sigma_2) s_{j|gb} s_{b|g} - 2(1-\lambda) s_j\big] & \text{if } k = j, l \in \mathcal{J}_{g'} \\[2ex]
\begin{aligned}
&- \frac{\alpha^2 s_j}{(1-\lambda)^2} \Big\{ \big[1 - \sigma_2 s_{j|gb} - \sigma_1(1-\sigma_2) s_{j|gb} s_{b|g} - 2(1-\lambda) s_j\big] \\
&\quad \times \big[\sigma_2 s_{k|gb} + \sigma_1(1-\sigma_2) s_{k|gb} s_{b|g} + (1-\lambda) s_k\big] \\
&\qquad - \big[\sigma_2 + \sigma_1(1-\sigma_2) s_{b|g}\big] s_{j|gb} s_{k|gb} \\
&\qquad\quad + \sigma_1(1-\sigma_2)^2 s_{j|gb} s_{b|g} s_{k|gb}(1 - s_{b|g}) \Big\}
\end{aligned} & \text{if } k \in \{\mathcal{J}_{gb} \setminus j\}, l = j \\[2ex]
\begin{aligned}
&\frac{\alpha^2 s_j}{(1-\lambda)^2} \Big\{ \big[\sigma_2 s_{k|gb} + \sigma_1(1-\sigma_2) s_{k|gb} s_{b|g} + (1-\lambda) s_k\big] \\
&\quad \times \big[\sigma_2 s_{k|gb} + \sigma_1(1-\sigma_2) s_{k|gb} s_{b|g} + 2(1-\lambda) s_k\big] \\
&\qquad - \big[\sigma_2 + \sigma_1(1-\sigma_2) s_{b|g}\big] s_{k|gb}(1 - s_{k|gb}) \\
&\qquad\quad - \sigma_1(1-\sigma_2)^2 s_{k|gb}^2 s_{b|g}(1 - s_{b|g}) - (1-\lambda) s_k \Big\}
\end{aligned} & \text{if } k \in \{\mathcal{J}_{gb} \setminus j\}, l = k \\[2ex]
\begin{aligned}
&\frac{\alpha^2 s_j}{(1-\lambda)^2} \Big\{ \big[\sigma_2 s_{k|gb} + \sigma_1(1-\sigma_2) s_{k|gb} s_{b|g} + 2(1-\lambda) s_k\big] \\
&\quad \times \big[\sigma_2 s_{l|gb} + \sigma_1(1-\sigma_2) s_{l|gb} s_{b|g} + (1-\lambda) s_l\big] \\
&\qquad + \big[\sigma_2 + \sigma_1(1-\sigma_2) s_{b|g}\big] s_{k|gb} s_{l|gb} \\
&\qquad\quad - \sigma_1(1-\sigma_2)^2 s_{k|gb} s_{b|g} s_{l|gb}(1 - s_{b|g}) \Big\}
\end{aligned} & \text{if } k \in \{\mathcal{J}_{gb} \setminus j\}, l \in \{\mathcal{J}_{gb} \setminus \{j, k\}\} \\[2ex]
\begin{aligned}
&\frac{\alpha^2 s_j}{(1-\lambda)^2} \Big\{ \big[\sigma_2 s_{k|gb} + \sigma_1(1-\sigma_2) s_{k|gb} s_{b|g} + 2(1-\lambda) s_k\big] \\
&\quad \times \big[\sigma_1(1-\sigma_2) s_{l|gb'} s_{b'|g} + (1-\lambda) s_l\big] \\
&\qquad + \sigma_1(1-\sigma_2)^2 s_{k|gb} s_{b|g} s_{l|gb'} s_{b'|g} \Big\}
\end{aligned} & \text{if } k \in \{\mathcal{J}_{gb} \setminus j\}, l \in \mathcal{J}_{gb'}, \\[2ex]
\tfrac{\alpha^2 s_j s_l}{1-\lambda} \big[\sigma_2 s_{k|gb} + \sigma_1(1-\sigma_2) s_{k|gb} s_{b|g} + 2(1-\lambda) s_k\big] & \text{if } k \in \{\mathcal{J}_{gb} \setminus j\}, l \in \mathcal{J}_{g'}
\end{cases}
$$

$$
\frac{\partial^2 s_j}{\partial p_l \partial p_k} =
\begin{cases}
-\dfrac{\alpha^2 s_j}{(1-\lambda)^2}\Big\{\big[1-\sigma_2 s_{j|gb}-\sigma_1(1-\sigma_2)s_{j|gb}s_{b|g}-2(1-\lambda)s_j\big] & \\
\qquad \times\big[\sigma_1(1-\sigma_2)s_{k|gb'}s_{b'|g}+(1-\lambda)s_k\big] & \\
\qquad\quad -\sigma_1(1-\sigma_2)^2 s_{j|gb}s_{b|g}s_{k|gb'}s_{b'|g}\Big\} & \\
 & \text{if } k\in\mathcal{J}_{gb'}, l=j \\[2ex]
\dfrac{\alpha^2 s_j}{(1-\lambda)^2}\Big\{\big[\sigma_1(1-\sigma_2)s_{k|gb'}s_{b'|g}+(1-\lambda)s_k\big] & \\
\qquad \times\big[\sigma_2 s_{l|gb}+\sigma_1(1-\sigma_2)s_{l|gb}s_{b|g}+2(1-\lambda)s_l\big] & \\
\qquad\quad +\sigma_1(1-\sigma_2)^2 s_{k|gb'}s_{b'|g}s_{l|gb}s_{b|g}\Big\} & \\
 & \text{if } k\in\mathcal{J}_{gb'}, l\in\{\mathcal{J}_{gb}\setminus j\} \\[2ex]
\dfrac{\alpha^2 s_j}{(1-\lambda)^2}\Big\{\big[\sigma_1(1-\sigma_2)s_{k|gb'}s_{b'|g}+(1-\lambda)s_k\big] & \\
\qquad \times\big[\sigma_1(1-\sigma_2)s_{k|gb'}s_{b'|g}+2(1-\lambda)s_k\big] & \\
\qquad\quad -\sigma_1(1-\sigma_2)s_{k|gb'}(1-s_{k|gb'})s_{b'|g} & \\
\qquad\qquad -\sigma_1(1-\sigma_2)^2 s_{k|gb'}^2 s_{b'|g}(1-s_{b'|g}) & \\
\qquad\qquad\quad -(1-\lambda)(1-\sigma_2 s_{k|gb'})s_k\Big\} & \\
 & \text{if } k\in\mathcal{J}_{gb'}, l=k \\[2ex]
\dfrac{\alpha^2 s_j}{(1-\lambda)^2}\Big\{\big[\sigma_1(1-\sigma_2)s_{k|gb'}s_{b'|g}+2(1-\lambda)s_k\big] & \\
\qquad \times\big[\sigma_1(1-\sigma_2)s_{l|gb'}s_{b'|g}+(1-\lambda)s_l\big] & \\
\qquad\quad +\sigma_1(1-\sigma_2)s_{k|gb'}s_{l|gb'}s_{b'|g} & \\
\qquad\qquad -\sigma_1(1-\sigma_2)^2 s_{k|gb'}s_{b'|g}s_{l|gb'}(1-s_{b'|g}) & \\
\qquad\qquad\quad +(1-\lambda)\sigma_2 s_k s_{l|gb'}\Big\} & \\
 & \text{if } k\in\mathcal{J}_{gb'}, l\in\{\mathcal{J}_{gb'}\setminus k\} \\[2ex]
\dfrac{\alpha^2 s_j}{(1-\lambda)^2}\Big\{\big[\sigma_1(1-\sigma_2)s_{k|gb'}s_{b'|g}+2(1-\lambda)s_k\big] & \\
\qquad \times\big[\sigma_1(1-\sigma_2)s_{l|gb''}s_{b''|g}+(1-\lambda)s_l\big] & \\
\qquad\quad +\sigma_1(1-\sigma_2)^2 s_{k|gb'}s_{b'|g}s_{l|gb''}s_{b''|g}\Big\} & \\
 & \text{if } k\in\mathcal{J}_{gb'}, l\in\mathcal{J}_{gb''} \\[2ex]
\tfrac{\alpha^2 s_j s_l}{1-\lambda}\big[\sigma_1(1-\sigma_2)s_{k|gb'}s_{b'|g}+2(1-\lambda)s_k\big] & \text{if } k\in\mathcal{J}_{gb'}, l\in\mathcal{J}_{g'} \\[1ex]
-\tfrac{\alpha^2 s_j s_k}{1-\lambda}\big[1-\sigma_2 s_{j|gb}-\sigma_1(1-\sigma_2)s_{j|gb}s_{b|g}-2(1-\lambda)s_j\big] & \text{if } k\in\mathcal{J}_{g'b''}, l=j \\[1ex]
\tfrac{\alpha^2 s_j s_k}{1-\lambda}\big[\sigma_2 s_{l|gb}+\sigma_1(1-\sigma_2)s_{l|gb}s_{b|g}+2(1-\lambda)s_l\big] & \text{if } k\in\mathcal{J}_{g'b''}, l\in\{\mathcal{J}_{gb}\setminus j\} \\[1ex]
\tfrac{\alpha^2 s_j s_k}{1-\lambda}\big[\sigma_1(1-\sigma_2)s_{l|gb'}s_{b'|g}+2(1-\lambda)s_l\big] & \text{if } k\in\mathcal{J}_{g'b''}, l\in\mathcal{J}_{gb'} \\[1ex]
-\tfrac{\alpha^2 s_j s_k}{1-\lambda}\big[1-\sigma_2 s_{k|g'b''}-\sigma_1(1-\sigma_2)s_{k|g'b''}s_{b''|g'}-2(1-\lambda)s_k\big] & \text{if } k\in\mathcal{J}_{g'b''}, l=k \\[1ex]
\tfrac{\alpha^2 s_j s_k}{1-\lambda}\big[\sigma_2 s_{l|g'b''}+\sigma_1(1-\sigma_2)s_{l|g'b''}s_{b''|g'}+2(1-\lambda)s_l\big] & \text{if } k\in\mathcal{J}_{g'b''}, l\in\{\mathcal{J}_{g'b''}\setminus k\} \\[1ex]
\tfrac{\alpha^2 s_j s_k}{1-\lambda}\big[\sigma_1(1-\sigma_2)s_{l|g'b'''}s_{b'''|g'}+2(1-\lambda)s_l\big] & \text{if } k\in\mathcal{J}_{g'b''}, l\in\mathcal{J}_{g'b'''} \\[1ex]
2\alpha^2 s_j s_k s_l & \text{if } k\in\mathcal{J}_{g'b''}, l\in\mathcal{J}_{g''}
\end{cases}
$$