Royalty Stacking and Standard Essential Patents: Theory and Evidence from the World Mobile Wireless Industry*

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Abstract

The royalty stacking hypothesis is based on the Cournot-complement model. It states that the royalties individually set by each standard essential patent holder (SEP holder) may add up to prohibitively high levels. We develop an equilibrium model with general log-concave constant-pass-through demand, downstream oligopoly and endogenous entry into manufacturing. Each SEP holder independently sets a linear royalty to maximize her individual profit.

The model shows that roughly 10 SEP holders suffice to significantly reduce equilibrium output; with 100 SEP holders output nearly collapses. As the number of SEP holders increases (i) the equilibrium price rises; (ii) quantity falls (iii) individual SEP holder's royalties and margins fall; and (iv) downstream manufacturing concentrates.

We look for evidence of royalty stacking in the world mobile wireless industry. The number of SEP holders for the widely deployed 2G, 3G, and 4G wireless cellular standards protractedly grew from 2 in 1994 to 130 in 2013. We find no evidence of royalty stacking. Between 1994 and 2013: (i) the number of devices sold each year rose 62 times or 20.1% per year on average; (ii) controlling for technological generation, the real average selling price of a device fell between −11.4% and −24.8% per year (iii) the introductory average selling price of successive generations fell over time; (iv) neither the average gross margin of SEP holders nor of non-SEP holders shows any trend; (v) the number of device manufacturers grew from one to 43; (vi) since 2001, concentration fell and the number of equivalent manufacturers rose from six to nine.

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1. Introduction

Most electronic devices we use—phones, personal computers, laptops, televisions or audio systems—rely on technological standards that make them interoperable. Technology standards enable the owner of an iPhone to call a friend subscribed to a different network who uses a Samsung Galaxy, switch to wifi when sitting in a cafe, or film a video and later watch it on her TV, laptop or tablet. And many firms design and manufacture components, devices, networks and applications. Yet an influential academic literature argues that technological progress in these industries is under threat because each owner of a standard-essential patent (SEP)—a patent that reads on an innovation that is potentially essential for the standard to work—can charge royalties far in excess of the patent's economic value to each manufacturer.

Royalty stacking is a direct application of the Cournot-complements model.[1] When many suppliers sell complementary inputs to downstream firms, act non cooperatively and set a linear price, they charge more for the bundle of inputs than a single monopolist would. This occurs because each supplier ignores that increasing her price reduces the profits of all other suppliers.

The analogy with SEPs is direct. A standard-compliant product uses hundreds, if not thousands of SEPs, owned by many different patent holders. It has been claimed that one excessive royalty will stack upon the other and together add up to an unsustainable high charge.[2] As Lerner and Tirole (2004) explain: "Under non-coordinated pricing, each licensor does not internalize the increase in the other licensors' profits when demand for the package is increased by a reduction in her price." Scholars and antitrust authorities have argued that royalty stacking slows down product introduction, increases prices paid by consumers and retards or might even derail the next round of innovation[3]. Worse, under severe royalty stacking the product market may collapse.

In this paper we contribute to this debate with both theory and evidence about the royalty stacking hypothesis. We focus on the widely used third generation (3G) and fourth generation (4G) wireless cellular standards defined by the third generation partnership project (3GPP). The effects

[1] Cournot (1897, ch. 9). As Gerardin, Layne Farrar and Padilla (2008) put it: "Royalty stacking is at its heart a reincarnation of the 'complements problem' first studied by the French engineer Agustin Cournot in 1838."

[2] As defined by Lemley and Shapiro (2007):

> The term "royalty stacking" reflects the fact that, from the perspective of the firm making the product in question, all of the different claims for royalties must be added or "stacked" together to determine the total royalty burden borne by the product if the firm is to sell that product free of patent litigation.

The Federal Trade Commission and the Department of Justice (2007, p. 61) defines royalty stacking as follows:

> Royalty stacking occurs when access to multiple patents is required to produce an end product, forcing the manufacturer's products "to bear multiple patent burdens," usually in the form of multiple licensing fees.

[3] About royalty stacking see, for example, Shapiro (2001), Lemley (2007), Lemley and Shapiro (2007), Miller (2007), Denicolo et al. (2008), Elhauge (2008), Gerardin, Layne-Farrar and Padilla (2008), Sidak (2008), Layne-Farrar and Padilla (2011), Layne-Farrar and Schmidt (2011), Rey and Salant (2012), Gupta (2013), Layne-Farrar (2014), Spulber (2013), Lerner and Tirole (2014), Schmidt (2014), Contreras and Gilbert (2015), Lerner and Tirole (2015) and Llobet and Padilla (2016). See also the more general theoretical analysis of Lerner and Tirole (2004).

of royalty stacking should be glaring in this industry because, as Figure 1 illustrates, during the last 20 years the number of SEP holders for 3G and 4G standards grew from 2 in 1994 to 130 in 2013 and the number of SEPs rose from a fewer than 150 in 1994 to more than 150,000 in 2013. Indeed, wireless cellular standards have been at the center of the debate about competitive harm due to high cumulative royalties.[4]

On the theory front we develop a model where manufacturers decide whether to enter and invest before each SEP holder individually and simultaneously sets her royalty. Then, taking the cumulative royalty as given, manufacturers compete in the product market by setting quantities and this determines the equilibrium quantity and price. On the supply side, we follow Genesove and Mullin (1998) and model the intensity of price competition with a conduct parameter, which nests most homogeneous-good oligopoly models. On the demand side, we use the family of log-concave, constant pass-through demand functions of Bulow and Pfleiderer (1983). As in Lerner and Tirole (2004, 2015) and Lemley and Shapiro (2007), this implies that willingness to pay is bounded and that the price elasticity of demand grows without bound as quantity goes to zero.

Our first result is already known: because each of the m SEP holders behaves as a monopolist, the Lerner margin is m times the Lerner margin that would be set by a monopolist who owns all SEPs (see Shapiro [2001] and Lerner and Tirole [2004]). Hence, regardless of the intensity of price competition and of the form of the demand curve, the cumulative royalty and the downstream equilibrium price increase with the number of SEP holders. Consequently, as royalty stacking worsens, the equilibrium quantity falls.

Nevertheless, we go beyond the extant literature and show that unless the demand curve is nearly vertical, royalty stacking reduces equilibrium output to a very small magnitude very fast, even with a modest number of SEP holders. So Cournot complements and royalty stacking are not about marginal effects. As claimed by the literature, the effect on industry performance can be devastating.

To see why, it is helpful to use Figure 1. It plots three constant rate of pass through, log-concave demand curves of the form

$$Q = S \cdot (v - p)^{\gamma},$$

where $v < \infty$ is the maximum willingness to pay, $\gamma > 0$ is a parameter that determines the curvature of the demand curve and S is a scale parameter chosen so that output is equal to 100 when price is equal to marginal cost. In this example (though not in the rest of the paper) we assume that downstream manufacturers are perfectly competitive, so with no patent rights price is equal to marginal cost. If patents are Cournot complements, each patent holder enjoys market power and

[4] For example, Lemley (2007) states:

> Time and time again, we have seen this sort of royalty-stacking problem arise. One great example is 3G telecom in Europe. The standard-setting organization (SSO) put out a call for essential patents, asking which they must license to make the 3G wireless protocol work and the price at which the patent owners would license their rights. 3G telecom received affirmative responses totaling over 6,000 essential patents and the cumulative royalty rate turned out to be 130%. This is not a formula for a successful product.

sets her royalty individually to maximize profits. If the demand curve is linear ($\gamma = 1$) and there are m patent holders, equilibrium output is equal to

$$\frac{100}{m+1}.$$

This expression implies, for example, that when only one patent holder charges a profit maximizing royalty rate (there is no royalty stacking), she reduces equilibrium output to 50, half the output that would be produced with marginal cost pricing. With the addition of a second patent holder, the cumulative royalty rises and output falls further, to 33.3, one-third relative to marginal cost pricing. By the time the number of patent holders reaches 10, output is 9.1—roughly 90 percent lower than with marginal cost pricing. And if the number of patent holders is 100, then output would be 1—99 percent lower than with marginal cost pricing and $\frac{1}{50}$th of output with one patent holder.

Of course, output falls at a slower rate when the demand curve is concave and $\gamma < 1$ and small. But then, we show that the equilibrium price is close to maximum willingness to pay v, even with only one patent holder and royalty stacking causes little incremental harm. So, royalty stacking theory has a rather extreme implication: either the industry nearly collapses with a modest number of patent holders or the the demand curve is close to vertical and royalty stacking is nearly irrelevant.

We also show that equilibrium individual royalties and SEP holders' margins *fall* with the number of SEP holders. As the number of SEP holders rises, the equilibrium downstream price rises and demand becomes more elastic. So each SEP holder prices less aggressively. Indeed, we show that the individual royalty charged by each SEP holder tends to zero with many SEP holders. So, and contrary to a rather widespread belief in the literature, evidence of excessive individual royalty rates suggests that there is no royalty stacking.

At the same time, as the number of SEP holders grows, the cumulative royalty rate extracts an increasing fraction of consumer willingness to pay. Indeed, with many SEP holders the cumulative royalty increases almost dollar by dollar with any exogenous shock that either increases willingness to pay or lowers downstream manufacturing costs. This occurs because with royalty stacking, equilibrium individual royalties are endogenous and adjust to extract any incremental surplus created by an exogenous shock. One implication is that the effects of royalty stacking cannot be undone in the data by "other" countervailing cost or quality shocks.

Last, as the number of SEP holders increases, fewer manufacturers enter and equilibrium industry concentration rises. Thus, prices rise and quantity falls further. Eventually, entry ceases and the downstream industry collapses if sales fall enough and the industry's net revenue becomes insufficient to pay for sunk entry costs.

We look for evidence of the observable implications of royalty stacking by examining the evolution of prices, quantities, gross margins, number of manufacturers and concentration in the world mobile wireless device industry between 1994 and 2013. As Figure 2 shows, between 1994 and 2007 the number of SEP holders grew from 2 to 130 and the number of declared SEPs grew more than 380 times.

Royalty staking theory predicts that, as the number of SEP holders grows, sales of phones will decline or, if quality increases demand and willingness to pay, at least stagnate. On the contrary, between 1994 and 2013 device sales grew. In 1994 the one manufacturer (Ericsson) sold 29 million devices. In 2013, by contrast, 43 manufacturers sold 1,810 million devices, a 62-fold increase, at an average rate of 20,1% per year. Moreover, successive generations of phones sell more devices than older ones. For example, manufacturers sold 782 million 3.5 G phones in 2013, the seventh year of that generation. This is the largest number of phones of any given generation sold during any given year.

Royalty staking theory predicts that, as the number of SEP holders grows, the price of a device will increase or (if quality increases demand) at least stagnate. On the contrary, between 1994 and 2013 and controlling for technological generation, the real average selling price of a device fell between -11.4% to -24.8% per year. Moreover, the introductory average selling price of successive generations fell.

Royalty stacking theory predicts that, as the number of SEP holders grows, SEP holders' and downstream manufacturers' margins will fall. We collected financial data on the universe of firms that participated in the development of the global third and fourth generation wireless cellular standards—over 300 firms— between 1994 and 2012 and for each computed gross margins year by year. The average gross margin of SEP holders hovers between 30% and 35%, but shows no downward trend. The average gross margin of non-SEP holders is higher and fluctuates more, but there is no sustained, long-run trend either.

Last, royalty stacking theory predicts that, as the number of SEP holders grows, the number of device manufacturers will decrease and industry concentration will rise. On the contrary, the number of device manufacturers grew from one in 1994 to 43 in 2013. And since 2001, concentration fell and the number of equivalent manufacturers rose from six to nine.[5,6]

Our paper is related to the literature on Cournot-complements. Spulber (2015) synthesizes this literature and shows that the Cournot-complement problem is an artifact of linear pricing. He shows that even with decentralized bargaining between suppliers and manufacturers, two-part tariffs are sufficient to make the problem disappear. We contribute to the Cournot-complement literature by showing, with a general class of demand functions and downstream oligopoly, that a finite and many times small number of suppliers suffice to worsen an industry's performance dramatically. We also show, in an appendix, that for the class of demand functions such that willingness to pay is unbounded (which includes the standard constant-elasticity demand) the market collapses when the number of input suppliers is equal to the price elasticity of demand. So we show that the Cournot complement theory is, in essence, a theory about a market failure, not about how a market works with multiple suppliers. In addition, we show that downstream double marginalization is a rather minor issue when there is a Cournot-complement problem—at most equal to one additional upstream supplier.

Our paper is also related to the literature on royalty stacking. Like Rey and Salant (2012),

[5] Let $\mathcal{H}$ be the Herfindahl index. The number of equivalent firms is equal to $\frac{1}{\mathcal{H}}$, or the number of firms of equal market shares that would produce the same Herfindahl index. See Adelman (1969).

[6] Market shares are measured with the number of devices sold, not value of sales.

Schmidt (2014), Lerner and Tirole (2004, 2015) we consider a model with upstream patent owners and downstream users needing access to the patents. We complement and generalize the linear demand model of Lemley and Shapiro (2007) and show that with almost any demand curve and downstream market structure, royalty stacking causes market collapse with a modest number of patent holders.[7] Also, we show that when there is a complement problem, vertical double marginalization is relatively less important.

As several other papers have pointed out, whether royalty stacking is slowing down innovation and hurting consumers of SEP-intensive goods has been rather controversial. While antitrust agencies and some recent court decisions on patent licensing cases have voiced concerns, the academic literature that has looked for evidence on royalty stacking has not made much progress by way of evidence.[8] For example, Teece and Sherry (2003), Gerardin, Layne-Farrar, and Padilla (2008), Gupta (2013), Spulber (2013), Layne-Farrar (2014), Barnett (2014, 2015) and Egan and Teece (2015) note that there is little empirical evidence about royalty stacking. Moreover, a recent empirical study by Galetovic, Haber and Levine (2015) found that over the past 16 years quality-adjusted prices of SEP-reliant products fell at rates are fast against patent-intensive, non-SEP-reliant products. Indeed, they fell fast relative to the prices of almost any other good, suggesting fast and sustained innovative activity. And they found that after the courts made it harder for SEP holders to hold-up manufacturing firms, the rate of innovation in SEP-reliant industries did not accelerate relative to other industries.[9] We add to this literature by showing that there is no evidence of royalty stacking in the mobile wireless industry either.

The rest of the paper is organized as follows. Section 2 provides some background of the role of SSOs and SEPs in the mobile wireless industry. Section 3 presents a long run equilibrium model of royalty stacking, and highlights some of the key observable implications from the model. Section 4 discusses evidence from the mobile wireless industry in relation to the key observable implications from the model. Section 5 concludes. We provide further results from the generalization of the model and further description of the data in Appendices A and B.

2. SSOs and SEPs in the mobile wireless industry

Standard setting organizations (SSOs) are industry groups formed to solve complex technical problems in different technology areas which address the needs of a large number of adopters. Standards are particularly important in the Information and Communications Technology (ICT) industry, where multiple devices need to connect and communicate with each other with interoperable technology. The development of a new technology begins in SSOs years before products reach the market.

Before there were wireless cellular standards, mobile phone users could not travel to another

[7] Recently, Llobet and Padilla (2016) have shown that royalty stacking is less severe with ad valorem than with per-unit royalties.

[8] For example, FTC (2011) and Judge Robart's decision on the Motorola vs. Microsoft (2012) case.

[9] There is a broad consensus in the legal literature that after the 2006 Supreme Court's *eBay Inc. v. MercExchange LLC* decision, firms that license their patents face greater difficulty in meeting the Supreme Court's "four-factor test" for a permanent injunction.

country and still make calls. Different technologies were used by different countries and firms, each requiring large investments. Thanks to technology standards, now the owner of smartphone A can talk with the owner of smartphone B—even though A and B are made by different manufacturers and operate on networks built and owned by different companies. More, smartphone A can also share pictures, videos, and other media at high speeds.

To achieve compatibility, the telecommunications industry organized itself around several SSOs. Most wireless systems deployed in the world today adopted the so-called third-generation (3G) and fourth-generation (4G) wireless cellular standards defined by a body called the Third Generation Partnership Project (3GPP).[10] 3GPP was formed in 1998 to develop a common wireless cellular system for Europe, Asia and North America. It brought together seven telecommunication SSOs and is responsible for generating the standards endorsed by the member SSOs. One of the seven SSOs, the European Telecommunications Standards Institute (ETSI), is in charge of the day-to-day management of 3GPP. Most firms participating in 3GPP are members of ETSI. Membership in 3GPP is voluntary (i.e. any firm can become a member), and members choose the technologies that become standards by consensus or by majority voting. Nearly 500 organizations participated in the development of these standards. Between 2005 and 2014 they spent around 3.5 million person-hours in around 850 working meetings.

In the evolution from 2G to 4G technologies, maximum download speeds increased about 12,000 times from 20 *kilo*bits-per-second in 2G to 250 *mega*bits-per-second in 4G. Standards also allow specialization (see Figure 3). Some firms develop communications technologies (the "IP innovators"). Others create products utilizing these technologies. Devices such as smartphones and tablets, and network infrastructure such as base stations and servers (the "manufacturers"). Yet others specialized in deploying large networks and providing the wireless services to consumers (the "operators" or "service providers").

One of the main functions of 3GPP is to develop IP rights (IPR) policies that foster investments in R&D. These policies develop the standard and facilitates fosters fast diffusion and adoption. Typically, the participants are allowed to seek IPR for their technical contributions and investments they make during the standardization process. This is an incentive to participate in and contribute to the standard development and setting.[11] SSOs usually require firms to declare the patents that are potentially essential to the implementation of the standards. Because all manufacturers who use a standard need a license from SEP holders, the IPR policies of several SSOs require their members to publicly declare any IPR that may become essential to the implementation of the standard, and to license them to any interested party on "fair, reasonable and non-discriminatory terms" (FRAND).[12] All seven SSOs that comprise 3GPP require firms to declare the patents that are potentially essential to the implementation of the standards. Firms declare their potentially

[10] Baron and Gupta (2015) describe and explain the process of 3GPP standard setting.

[11] Some standards bodies produce open standards, i.e., participants forfeit their iIPR when contributing a technology into the standard, while others produce entirely proprietary standards, i.e., standards controlled by a single firm or a group of entities.

[12] Although the IPR policies vary widely, FRAND terms are a common practice in the most commonly used ICT standards for wireless technologies. For a recent survey of IPR policies across SSOs, see Bekkers and Updegrove (2012).

essential patents by filling declaration forms,which are maintained in a database by ETSI.

Figure 2 shows the time series of the number of SEPs and the number of firms owning these SEPs. During the last 20 years the number of SEP holders for 3G and 4G standards grew from 2 in 1994 to 130 in 2013 and the number of SEPs rose from fewer than 150 in 1994 to more than 150,000 in 2013. The number of SEPs, or complementary inputs for producing mobile wireless products, and the number of firms owning SEPs has been increasing over time Thus, if a royalty stacking problem exists, it should be worsening over time.

3. A long-run equilibrium model of royalty stacking

3.1. A roadmap

In this section we present a simple equilibrium model of royalty stacking with endogenous entry and investment. Our aim is to compare the long-run equilibrium of an industry with and without royalty stacking.

The model is a standard, three stage, exogenous sunk cost game with endogenous entry (see Sutton [1991]) and the time line is described in Figure 4. In the first stage (Entry, $t = 0$), manufacturers enter and invest. In the second stage (Royalties, $t = 1$) each SEP holder sets individually and non-cooperatively a linear royalty. In the third stage (Competition, $t = 3$) each manufacturer chooses her quantity individually and non-cooperatively. We now describe the model.

3.2. The model

Demand Following Genesove and Mullin (1998) we assume that the demand for phones, D, is of the form

$$Q = D(p) \equiv S \cdot (v - p)^{\gamma}\,, \tag{3.1}$$

with $\gamma > 0$. Here Q and p have obvious meanings and S is the size of the market.[13] Note that the inverse demand is $P \equiv D^{-1}$,with

$$P(Q) = v - \left(\frac{Q}{S}\right)^{\frac{1}{\gamma}}.$$

When $\gamma, v > 0$, this demand function nests, as special cases, the linear demand used by Lemley and Shapiro (2007) ($\gamma = 1$); the quadratic demand curve ($\gamma = 2$); and the exponential demand function when $v, \gamma \to \infty$ with $\frac{\gamma}{v}$ constant. It is strictly concave if $\gamma \in (0, 1)$ and strictly convex if $\gamma > 1$. Regardless, it has the appealing property that, with the exception of the limiting exponential demand, willingness to pay is finite and bounded from above by v. Also, note that

$$\frac{d\frac{D'}{D}}{dp} = -\frac{\gamma}{(v-p)^2} < 0. \tag{3.2}$$

[13] Farbinger and Weyl (2013) call this the constant pass-through class of demand functions due to Bulow and Pfleiderer (1983).

Now this property implies that D is log concave.[14] This ensures quasi concave profit functions and reaction curves with standard properties. Now the price elasticity is

$$\eta(p) = \gamma \frac{p}{v-p},$$

which increases with price. Moreover,

$$\frac{d\eta}{dp} = -\left(\frac{D'}{D} + p \cdot \frac{d\frac{D'}{D}}{dp}\right) = \frac{v}{(v-p)^2} > 0 \tag{3.3}$$

and

$$\lim_{p \to v} \eta(p) = \gamma \cdot \lim_{p \to v} \frac{p}{v-p} = \infty. \tag{3.4}$$

So property (3.2) implies that with bounded willingness to pay, the price elasticity of demand η is increasing in p and unbounded. This is a fact is of some importance below.

Remark 1. *Our demand function is similar to the formulations used by Lerner and Tirole (2004 and 2015). Parameter v in our specification is willingness to pay, and is similar to their function V. In their (2004) paper V is an increasing function of the number of innovations; in their (2015) paper V is a function of the number of functionalities. Functionalities are modeled as a finite set I and a subset $S \subseteq I$ of functionalities is a standard. Our formulation can be readily extended in that direction. Indeed, one surmises that v increases over time as new phones add functionalities and features and improve in quality (see section 3.4.3).*

Remark 2. *Like us, Lerner and Tirole (2004, p. 693 and 2015, p.552) assume bounded willingness to pay, and their demand functions also exhibit property (3.2). This implies that the elasticity of demand is increasing in price and $\lim_{p \to V} \eta(p) = \infty$ (our properties 3.3 and 3.4).*

Remark 3. *In the Appendix we consider the family of demand functions*

$$Q = D(p) \equiv S \cdot (v+p)^{\gamma}, \tag{3.5}$$

with $\gamma < 0$ and $v \in \mathrm{IR}$. When $v = 0$ this is the traditional constant-elasticity demand with $\eta = -\gamma$. Note that now willingness to pay increases without bound as Q falls. By contrast,

$$\lim_{p \to \infty} \eta(p) = -\gamma \cdot \lim_{p \to \infty} \frac{p}{v+p} = -\gamma,$$

hence the price elasticity of demand is bounded as p rises (or Q falls). Again, this fact is of some importance below because, as will be seen, it suggests that this class of demand functions is inappropriate to analyze royalty stacking.

[14] See Corollary 1 in Bagnoli and Bergstrom (2005). As Cowan (2004) shows, log-concavity means that demand is no more convex than an exponential function. Not coincidentally, the limiting demand curve of the form (3.1) as $\gamma \to \infty$ is the exponential demand.

Manufacturers To enter the industry each manufacturer must invest σ to produce each unit of the final good at constant long-run marginal cost c, Each manufacturer pays a linear royalty $\mathcal{R}$ per unit of output.

SEP holders There are m SEP holders. Each SEP reads on an invention that cannot be invented around and all inventions are complements.[15] The cost to a SEP holder per unit (for making and selling its components or licensing its patent) is c_ℓ per unit. Each SEP holder charges a per-unit, linear royalty r_j. Thus $\mathcal{R} = \sum r_j$ is the cumulative royalty and mc_ℓ the per-unit cumulative licensing cost. To ensure that an equilibrium with production exists when there is no stacking and one licensee for all patents, we assume that $v - c - c_\ell > 0$.[16]

Remark 4. *Lerner and Tirole (2015, p. 252) introduce a "within functionality competition index," which caps the royalty that a SEP holder can charge ("dominant IP owner" in their terminology). This models the possibility that a manufacturer may substitute another patent for an SEP at a cost, even after the standard has been agreed and set. In our framework, this would be equivalent to assume that* $r_j \leq \bar{r}_j$.

Short-run competition Downstream competition is imperfect. We follow Genosove and Mullin's (1998) variation on Bresnahan (1989). The equilibrium oligopoly quantity is characterized is characterized by the generalization of the monopolist's first-order condition. So in the short-run, symmetric equilibrium, each firm chooses its output q_i so that the equilibrium condition

$$P(Q) + \theta q_i P'(Q) = c + \mathcal{R}, \tag{3.6}$$

holds, where θ is the conduct or market power parameter. This nests most static oligopoly models. As is well known, when $\theta = 0$, there is perfect competition; $\theta = n$ yields monopoly pricing; and $\theta = 1$ yields Cournot competition. Our aim in using this general structure is to examine the robustness of our results to alternative market conducts.

Timing The timing of the dynamic game is shown in Figure 4. In the first stage (Entry, $t = 0$) n manufacturers invest σ. In the second stage (Royalties, $t = 1$), each SEP holder j simultaneously and independently chooses r_j taking the number of SEP holders, vector $\mathbf{r}_{-j}$ of royalties and industry structure as given. In the last stage (Competition, $t = 2$) each downstream manufacturer

[15] This follows the definition of essentiality given, for example, byAssistant Attorney General Joel Klein:

> Essential patents, by definition, have no substitutes; one needs licenses to each of them in order to comply with the standard.

Letter of Joel I. Klein to R. Carey Ramos, Esq., June 10, 1999, http://www.usdoj.gov:80/atr/public/busreview/2485.wpd. Cited in Lerner and Tirole (2004)

[16] Note that we assume that inventions do not add any value. Assuming that inventions add no value is extreme, but many authors argue that stacking occurs in part because patents which add little or no value are used to hold up manufacturers. One can model valuable patents assuming that v is an increasing function of m.

simultaneously sets q_i, given n and $\mathcal{R}$. So our model is an exogenous sunk cost game with endogenous entry, where the conduct parameter θ indexes the intensity of price competition (see Sutton (1991)).

In what follows we first solve the equilibrium entry game among manufacturers, taking the cumulative royalty as given (section 3.3). Next we compute the equilibrium royalty with royalty stacking, and examine their effect on the long-run performance of the industry (section 3.4).

3.3. Downstream equilibrium with endogenous entry

3.3.1. Competition in the product market

We begin with the last stage of the game. Then manufacturers take n and $\mathcal{R}$ as given and each solves

$$\max_{q_i} \{q_i [P(Q) - (c + \mathcal{R})]\}.$$

Standard manipulations of the first order condition (3.6) yields that in a symmetric equilibrium

$$p = \frac{\theta v + \gamma n(c + \mathcal{R})}{\theta + \gamma n}. \tag{3.7}$$

$$Q = S\left(\frac{\gamma n}{\theta + \gamma n}\right)^{\gamma} \cdot [v - (c + \mathcal{R})]^{\gamma}; \tag{3.8}$$

Equation (3.7) shows the standard price-concentration relationship:

$$\frac{\partial p}{\partial n} = -\frac{\theta\gamma}{(\theta + n\gamma)^2}[v - (c + \mathcal{R})] < 0. \tag{3.9}$$

So, the price falls as the number of firms increases and concentration falls.[17] Moreover, equations (3.7) and (3.8) show a basic relationship: with a higher royalty $\mathcal{R}$, the equilibrium price rises and quantity falls. The price also falls with θ (the more intense price competition is) and with γ (the more elastic the demand for the good), ceteris paribus. Last, note that the pass-through rate of royalties is

$$\frac{\partial p}{\partial \mathcal{R}} = \frac{\gamma n}{\theta + \gamma n} \leq 1. \tag{3.10}$$

As is well known, the rate of pass through is dollar-for dollar with perfect competition ($\theta = 0$) and constant marginal cost. With imperfect competition the rate of pass through is less than dollar for dollar for demand functions with $\gamma > 0$, but increases with the number of manufacturers.

In what follows margins are important. The standard price-cost equilibrium margin is

$$\mu \equiv p - (c + \mathcal{R}) = \frac{\theta}{\theta + \gamma n}[v - (c + \mathcal{R})]. \tag{3.11}$$

Thus manufacturers appropriate part of the difference between marginal cost and willingness to pay. The Lerner margin is

$$\mathcal{L} \equiv \frac{p - (c + \mathcal{R})}{p} = \frac{\theta v - \theta(c + \mathcal{R})}{\theta v + \gamma n(c + \mathcal{R})}. \tag{3.12}$$

[17] In a symmetric equilibrium $\frac{1}{n}$ is the Herfindahl index.

One may be tempted to study the effects of royalty stacking with this simple one-period model. Whether appropriate depends on your view of the magnitude of the royalty stacking problem, however. If royalty stacking is one of many things going on in the industry, the short-run game is probably appropriate and the effects of higher cumulative royalties are rather straightforward: higher cumulative royalties increase the equilibrium price, reduce the total quantity sold and reduce manufacturer's margins and profits. By contrast, if royalty stacking is an overwhelming force in the industry, it is necessary to consider its effect on entry and structure. So next we model equilibrium entry.

3.3.2. Entry

In the long run, the zero-profit entry condition holds:

$$\mu^* \frac{Q^*}{n^*} \equiv [p^* - (c + \mathcal{R})] \frac{Q^*}{n^*} = \sigma; \tag{3.13}$$

(we use a star * to denote long run equilibrium values). Condition (3.13) just says that margins times volume must cover sunk entry costs.

We now solve the entry game. When entering, firms anticipate the short-run game they will play. Hence, substituting (3.8) and (3.11) into (3.13) and rearranging yields

$$\left(\frac{\theta}{\theta + \gamma n^*}\right) \cdot \left(\frac{\gamma n^*}{\theta + \gamma n^*}\right)^{\gamma} [v - (c + \mathcal{R})]^{\gamma+1} \cdot \frac{S}{n^*} = \sigma.$$

Now rearrange this expression as

$$\frac{S}{\sigma} \cdot \theta \cdot [v - (c + \mathcal{R})]^{\gamma+1} = n^* \cdot (\theta + \gamma n^*) \cdot \left(\frac{\theta + \gamma n^*}{\gamma n^*}\right)^{\gamma} \equiv \phi(n^*; \theta, \gamma). \tag{3.14}$$

To appreciate the mechanics behind condition (3.14), it is useful to consider a linear demand ($\gamma = 1$) and Cournot competition ($\theta = 1$). Then the right hand side of the condition is

$$\phi(n^*) = (1 + n^*)^2,$$

which is increasing in n^*. Thus, with linear demand and Cournot competition anything that increases the size of the left-hand side also increases the equilibrium number of manufacturers, and the equilibrium number of firms is increasing in the ratio of market size S relative to the entry cost σ—the larger the market relative to the entry cost σ, the more manufacturers enter in equilibrium. Also, the number of firms is increasing in θ: the less intense is price competition, the more manufacturers enter in equilibrium. Last, the number of firms is increasing in $v-(c+\mathcal{R})$—the more value added per unit, the more manufacturers enter. For the same reason, a higher cumulative royalty $\mathcal{R}$ reduces the equilibrium number of firms, ceteris paribus.

Result 3.1. *In the long run a higher cumulative royalty concentrates the market.*

Now some tedious Algebra shows that $\phi'(n^*) > 0$.[18] Hence the same relationships hold, regardless of γ and θ. We conclude that any parametric change that increases the left-hand side of (3.14) increases the number of firms and lead to a less concentrated industry in equilibrium; and any parametric change that decreases the left-hand side of (3.14) will decrease the number of firms and lead to a more concentrated industry.

3.3.3. Prices, quantities and concentration

We now return to the product market to derive the long-run relationship between cumulative royalties and observable market variables. We consider an exogenous increase of $\mathcal{R}$, the cumulative royalty . Totally differentiating both sides of (3.14) and rearranging yields

$$\frac{\partial n^*}{\partial \mathcal{R}} = -\frac{(\gamma+1)\frac{\theta S}{\sigma}\left[v-(c+\mathcal{R})\right]^{\gamma}}{\phi'(n^*)} < 0.$$

Result 3.2 (Royalties and concentration). *In the long run, higher cumulative royalties $\mathcal{R}$ reduce the equilibrium number of firms and increase concentration.*

To see how prices vary with an exogenous increase of $\mathcal{R}$, replace n^* into (3.7), totally differentiate with respect to $\mathcal{R}$ and rearrange. This yields

$$\frac{\partial p^*}{\partial \mathcal{R}} = \frac{\gamma n^*}{\theta+\gamma n^*} - \frac{\theta\gamma}{(\theta+\gamma n^*)^2}\left[v-(c+\mathcal{R})\right]\frac{\partial n^*}{\partial \mathcal{R}} > 0 \tag{3.15}$$

The impact of higher royalties on the long-run equilibrium price is the sum of two terms: first, the short run pass through rate $\frac{\gamma n^*}{\theta+\gamma n^*}$; second, higher cumulative royalties increase concentration, the industry moves along the price-concentration relationship and prices rise—the second term in (3.15).

Similarly, to see how quantity varies with an exogenous change in $\mathcal{R}$, totally differentiate (3.8):

$$\frac{\partial Q^*}{\partial \mathcal{R}} = -\frac{Q^*}{v-(c+\mathcal{R})} + \frac{\theta}{n^*}Q^*\frac{\partial n^*}{\partial \mathcal{R}} < 0. \tag{3.16}$$

So the impact on the long-run equilibrium quantity is the sum of a short run effect, $\frac{Q^*}{v-(c+\mathcal{R})}$; and a long run effect—prices rise in a more concentrated industry and quantities fall even further. Hence:

Result 3.3 (Prices, quantities and concentration). *In the long run, higher cumulative royalties increase the equilibrium price, reduce the equilibrium quantity sold and concentrates the industry ceteris paribus.*

---

[18] Indeed,

$$\frac{d\phi}{dn} = \frac{(\theta+n\gamma)^{\gamma}}{(n\gamma)^{\gamma}}\left([\theta+\gamma(2n-\theta)]\right) > 0,$$

because, $\theta \leq n$ with equality only when manufacturers price as a monopoly.

How general is Result 3.3? When the cumulative royalty rises exogenously, the long run equilibrium price rises and the long-run equilibrium quantity falls with any plausible demand curve.

The increase in concentration is slightly less general, but still very likely. To see why, recall that in equilibrium per-firm profits equal

$$\mu^* \frac{Q^*}{n^*} = [p^* - (c + \mathcal{R})] \frac{Q^*}{n^*} = \sigma.$$

Thus, concentration increases when the higher cumulative royalty reduces per firm profits with fixed n. In the model, this must occur because a higher cumulative royalty reduces the margin μ^* and the total quantity sold.

Remark 5. *As is well known, for the family of demand curves (3.5), which exhibits unbounded willingness to pay, the short run rate of pass trough is greater than one—the short run equilibrium price μ rises more than dollar by dollar with a higher $\mathcal{R}$—and per firm profits may rise with a higher royalty. In that case a higher cumulative royalty would stimulate entry. Nevertheless, as we show in the Appendix, a necessary condition for this is that $\lim_{p\to\infty} \eta(p) = -\gamma < 1$ in (3.5). Moreover, with m SEP holders, an equilibrium with a finite royalty and some sales exists only if $-\gamma > m$, which is ruled out by $-\gamma < 1$. Thus, we can safely ignore this case.*

3.3.4. Margins and royalties

We now turn to margins. Simple differentiation yields that

$$\frac{\partial \mu^*}{d\mathcal{R}} = -\frac{\theta}{\theta + \gamma n^*} + \frac{\gamma\theta\,[v - (c + \mathcal{R})]}{(\theta + \gamma n^*)^2} \frac{\partial n^*}{\partial \mathcal{R}} \lesseqgtr 0$$

In the short run margins fall, because the rate of pass through is less than dollar by dollar. In the long run, however, the industry concentrates, and the equilibrium price rises, which tends to raise margins. Hence:

Result 3.4. *In the long run, higher royalties have an ambiguous effect on long-run margins.*

Similarly, the change in the Lerner margin of each manufacturer is

$$\begin{aligned}
\frac{\partial \mathcal{L}^*}{\partial \mathcal{R}} &= \frac{1}{p}\left(\frac{\partial \mu^*}{\partial \mathcal{R}} - \frac{\partial p^*}{\partial \mathcal{R}}\mathcal{L}^*\right) \\
&= \frac{1}{p}\left[(1 - \mathcal{L}^*)\frac{\partial p^*}{\partial \mathcal{R}} - 1\right] \\
&= -\frac{\theta v(\theta + \gamma n^*)}{[\theta v + \gamma n^*(c + \mathcal{R})]^2} + \frac{\gamma\theta[v - (c + \mathcal{R})]}{(\theta v + \gamma n^*(c + \mathcal{R}))^2}(c + \mathcal{R})\left(-\frac{\partial n^*}{\partial \mathcal{R}}\right) \lesseqgtr 0.
\end{aligned}$$

Again, this is ambiguous (and a bit messy). Nevertheless, a sufficient condition for Lerner margins to fall is that the long-run rate of pass through is dollar-by-dollar or less. It can be shown that this will hold whenever production per firm, $\frac{Q^*}{n^*}$ does not fall as the industry concentrates.

3.4. Royalty stacking

3.4.1. The SEP holders' game

The SEP holder's decision When setting her royalty each upstream SEP holder takes m and downstream behavior as given, and solves

$$\max_r \{(r - c_\ell) \times D(p)\}. \tag{3.17}$$

Call r_m^j SEP holder j's optimal individual royalty with m SEP holders and $\mathcal{R}_m$ the cumulative royalty. The first order condition is

$$(r_m^j - c_\ell) \times D'(p)\frac{\partial p}{\partial \mathcal{R}} + D(p) = 0.$$

Now in a symmetric equilibrium $r_m^j = r_m$ and $\mathcal{R}_m = mr_m$. Then the first order condition can be rewritten as

$$\frac{r_m - c_\ell}{r_m} \times \frac{D'(p)}{D(p)}p \times \frac{\partial p}{\partial \mathcal{R}}\frac{\mathcal{R}_m}{p}\frac{1}{m} + 1 = 0$$

Now define $\epsilon_m = \frac{\partial p}{\partial \mathcal{R}}\frac{\mathcal{R}_m}{p}$ as the elasticity of downstream equilibrium prices with respect to the royalty . After some manipulations,

$$\frac{r_m - c_\ell}{r_m} = \frac{m}{\epsilon_m \eta}. \tag{3.18}$$

Because $\mathcal{R}_m = mr_m$, it follows that

$$\frac{\mathcal{R}_m - mc_\ell}{\mathcal{R}_m} = \frac{m}{\epsilon_m \eta} > \frac{1}{\epsilon_m \eta} = \frac{\mathcal{R}_1 - mc_\ell}{\mathcal{R}_1}.$$

This is the well-known Cournot complements result: each SEP holder "sees" the market demand of the final good and acts as a monopoly.[19] The consequence is that m monopolists "stack" their royalties and they charge m times the Lerner margin that would be set by a monopoly licensing all patents.[20]

Now it is useful to rewrite (3.18) as

$$r_m = \frac{\epsilon_m \eta}{\epsilon_m \eta - m} c_\ell. \tag{3.19}$$

[19] See Shapiro (2001), Lerner and Tirole (2004, p. 695) and Proposition 4(ii) in Lerner and Tirole (2015).

[20] Shapiro (2001, p. 150) assumes perfect competition downstream. With perfect competition $\epsilon_m = 1$ and

$$\frac{\mathcal{R}_m - mc_\ell}{\mathcal{R}_m} = \frac{m}{\eta} > \frac{1}{\eta} = \frac{\mathcal{R}_1 - c_\ell}{\mathcal{R}_1}.$$

Also, let p^m be the downstream equilibrium price with m SEP holders. With perfect competition $p^m = c + \mathcal{R}_m$. Straightforward manipulations imply that

$$\frac{p^m - (c + mc_\ell)}{p^m} = \frac{m}{\eta} > \frac{1}{\eta} = \frac{p^1 - (c + mc_\ell)}{p^1},$$

which is the condition shown by Shapiro.

Equation (3.19) might suggest that in equilibrium the individual royalty rises with the number of SEP holders. Nevertheless, when willingness to pay is bounded, the price elasticity of demand increases with p, so that r_m may fall with m, as we will see it is indeed the case.[21]

Royalty stacking and the individual royalty We now return to the model. Some algebra yields that the individual royalty is

$$r_m = \frac{(v-c)+\gamma c_\ell}{m+\gamma}. \tag{3.20}$$

It is apparent that the equilibrium individual royalty decreases with m. Thus, as the number of SEP holders increases and royalty stacking worsens, one should observe SEP holders charging lower individual royalties, ceteris paribus.

Result 3.5 (Royalty stacking and individual royalties). *With bounded willingness to pay the individual royalty is decreasing in the number of SEP holders. Moreover, the individual royalty tends to zero as the number of SEP holder becomes large.*

It might be somewhat surprising that individual royalties fall with the number of SEP holders—after all, holdup is supposed to yield excessive individual royalties. To discuss the economics, note that SEP holder's profit equals her margin times the cumulative quantity sold by manufacturers,

$$(r_j - c_\ell) \times D(p).$$

In equilibrium, she optimizes and

$$\left[D(p) + (r_m - c_\ell)D'(p)\frac{\partial p}{\partial \mathcal{R}}\right] dr_j = 0.$$

When a SEP holder marginally decreases her royalty in $dr_j < 0$, her revenues fall in $D(p)dr_j$; but as the downstream price falls in

$$\frac{\partial p}{\partial \mathcal{R}} dr_j$$

(the rate of pass through times the royalty change), her revenue increases by

$$(r_j - c_\ell)D'(p)\frac{\partial p}{\partial \mathcal{R}} dr_j.$$

In equilibrium, each SEP holder optimally balances this trade off, so that both effects are of equal size but opposite sign.

[21] It can be shown that when willingness to pay is unbounded, the individual royalty rate grows with m and tends to a very large number very fast. To see why, note that when willingness to pay is unbounded, the price-elasticity of demand tends to a bound equal to $-\gamma$. Moreover, it can be shown that $\epsilon_m < 1$. Hence, as the number of SEP holders grows, $\epsilon_m \eta - m$ should tend to 0 fast, unless η is very large. To get a feel of how large is "large," note that the number of SEP holders is about 130 in 2013 in the mobile wireless industry. An equilibrium with production would require an almost infinitely elastic demand. Such is unlikely. Therefore, we ignore the family of demands (3.5), and relegate its analysis to Appendix A.

Now assume an additional SEP holder appears, charges r_m and everybody else keeps charging r_m. Then the equilibrium downstream price increases in $\frac{\partial p}{\partial \mathcal{R}} r_m$. Quantity falls, and so does the loss of marginally decreasing the individual royalty . At the same time, depending on the sign of D'', the gain from slightly lowering the royalty may fall or rise. But if willingness to pay is bounded, it can be shown that the magnitude D' falls by less than D. Hence

$$D\left(p + \frac{\partial p}{\partial \mathcal{R}} r_m\right) + (r_m - c_\ell) D'\left(p + \frac{\partial p}{\partial \mathcal{R}} r_m\right) \frac{\partial p}{\partial \mathcal{R}} < 0.$$

and every SEP holder decreases her royalty as m increases.[22]

Royalty stacking and SEP holders' margins Some further Algebra yields that the equilibrium price-cost margin of each SEP holder is

$$r_m - c_\ell = \frac{1}{m+\gamma} \left[(v-c) - mc_\ell)\right],$$

while the corresponding equilibrium Lerner margin is

$$\mathcal{L}_m = \frac{r_m - c_\ell}{r_m} = \frac{(v-c) - mc_\ell}{v - c + c_\ell}.$$

Thus:

Result 3.6. *If willingness to pay is bounded, then SEP holders' Lerner margins fall as the number of SEP holders rises.*

Royalty stacking and the cumulative royalty Consider now the cumulative royalty :

$$\mathcal{R}_m = mr_m = \frac{m}{m+\gamma} \left[(v-c) + \gamma c_\ell\right]; \tag{3.21}$$

as m increases and one royalty stacks upon the other, the cumulative royalty $\mathcal{R}$ increases with the number of SEP holders.

Result 3.7 (Royalty stacking and the aggregate royalty). *In the long run, the cumulative royalty increases with the number of SEP holders.*

[22] Note that

$$\text{ms} \equiv P'Q = \frac{p}{\eta} = \frac{D}{D'}$$

is the marginal surplus function (see Appendix A). Then the equilibrium condition can be rewritten as

$$\left[1 - (r_m - c_u)\frac{1}{\text{ms}(p)} \frac{\partial p}{\partial \mathcal{R}}\right] D(p) dr_j.$$

With bounded willingness to pay and constant rate of pass through, marginal surplus is decreasing as p rises. By contrast, for the family of demand functions such that willingness to pay is unbounded, $\text{ms}(p)$ is increasing (see the Appendix) and the optimal individual royalty rate increases with stacking. As we have already mentioned, however, such a family of functions has rather implausible implications.

Comparative statics The results that we have obtained so far on royalty stacking hold keeping "everything else" constant. Nevertheless, when we look at the performance of the mobile wireless industry over the last two decades, "everything else" was not constant. In particular, the quality of mobile phones has increased, raising willingness to pay v; and the manufacturing cost c has probably fallen. Nevertheless,

$$\frac{\partial \mathcal{R}_m}{\partial v} = -\frac{\partial \mathcal{R}_m}{\partial c} = \frac{m}{m+\gamma}.$$

Thus, when m is large, the cumulative royalty increases nearly dollar by dollar with willingness to pay; it also increases almost dollar by dollar when manufacturing costs fall.

Result 3.8. *When the number of SEP holders is large, the cumulative royalty changes almost dollar-by-dollar with v and c.*

An important implication of this result is that the effect of higher royalties wrought by stacking on prices cannot be undone by higher willingness to pay or lower manufacturing costs. Essentially, SEP holders acting with an objective function like (3.17) increase their royalty when v increases or c falls. Because the cumulative royalty does not depend on the market scale parameter S, neither do the implications on pricing change when market size exogenously increases, for example because the income elasticity is large and income grows. So:

Result 3.9. *When the number of SEP holders is large and there is royalty stacking, the equilibrium price will not fall with falling costs. Similarly, quality increases will increase the cumulative royalty and equilibrium prices.*

3.4.2. How harmful is royalty stacking?

Many think that royalty stacking is harmful and several authors have proposed amendments to the standard setting process to prevent it[23]. As Lerner and Tirole (2014, p. 973) put it: "In recent years antitrust authorities have wakened to the importance of standardization and the way in which firms can manipulate this process."

One way to measure the harm caused by royalty stacking is to quantify the fall in industry output it causes. To do this, recall that the demand curve is

$$Q = S \cdot (v-p)^{\gamma}.$$

Some algebra shows that with royalty stacking by m SEP holders,

$$v - p = \frac{n\gamma}{\theta + n\gamma} \cdot \frac{\gamma}{m+\gamma} \cdot (v - c - mc_{\ell}). \tag{3.22}$$

So

$$Q_m = \left(\frac{n\gamma}{\theta + n\gamma}\right)^{\gamma} \left(\frac{\gamma}{m+\gamma}\right)^{\gamma} \cdot \left[S(v - c - mc_{\ell})^{\gamma}\right] \tag{3.23}$$

[23] See, for example, Lerner and Tirole (2014, 2015) and Lemley and Shapiro (2013).

is the equilibrium quantity.

The term in brackets is the quantity that would be sold when neither patent holders nor manufacturers exercise any market power and $p = c + mc_\ell$; this serves as a benchmark. The first parenthesis measures the effect of double marginalization on the equilibrium quantity. The second parenthesis in (3.23) measures the effect of royalty stacking with m SEP holders.

Double marginalization disappears when the downstream market is perfectly competitive, for then $\theta = 0$ and $\frac{n\gamma}{\theta+n\gamma} = 1$. On the other hand, if downstream firms price as a monopoly, then $\theta = n$ and

$$\frac{n\gamma}{\theta + n\gamma} = \frac{\gamma}{1+\gamma}.$$

It follows that the size of the double marginalization effect is at most like adding one additional patent holder. So with severe royalty stacking, the double marginalization effect is not very important.

Result 3.10. *At worst, the double marginalization effect is like adding one more patent holder to the royalty stack.*

Now it is apparent that for $m \geq 1$

$$[S(v - c - c_\ell)^\gamma] \geq Q_1 \geq Q_m.$$

To measure the relative magnitude of the royalty-stacking effect, define

$$\mathcal{Q}(Q) \equiv \frac{Q}{S(v - c - mc_\ell)^\gamma} \cdot 100. \tag{3.24}$$

This ratio shows quantity Q as a fraction of output with $p = c + mc_\ell$ —the optimal short-run output when no royalties are charged and there is perfect competition downstream. Then

$$\mathcal{Q}(Q_m) = \frac{Q_m}{S(v - c - mc_\ell)^\gamma} \cdot 100 = \left(\frac{n\gamma}{\theta + n\gamma}\right)^\gamma \left(\frac{\gamma}{m+\gamma}\right)^\gamma \cdot 100 < 100. \tag{3.25}$$

With $m = 1$ there is no royalty stacking.

Figure 5 plots ratio (3.25) with four different values of γ, assuming that nine manufacturers ($n = 9$) compete à la Cournot ($\theta = 1$) in the downstream market[24]. Consider first $\gamma = 1$ —the linear demand function which was used by Lemley and Shapiro (2007). As the black line in Figure 5 shows, with $m = 1$ (no royalty stacking) $\mathcal{Q}(Q_1) = 45$. This combines monopoly pricing (which reduces output by half with linear demand) and Cournot double marginalization (which further reduces equilibrium output to 45). Royalty stacking further reduces equilibrium output, and very fast: with $m = 10$ SEP holders, output falls to 8.2; with $m = 50$ output falls to 1.8 and with $m = 100$ output falls to 0.9.

Now with $\gamma = 1.5$ demand is more elastic at each price, and output falls even faster as m grows; with $\gamma = 0.5$, demand is less elastic at each price, and output falls a bit slower. But in

[24] As we show in section 4, in 2013 the number of equivalent manufacturers was 9. Let $\mathcal{H}$ be the Herfindahl index. The number of equivalent firms equals $\frac{1}{\mathcal{H}}$; see Adelman (1969).

both cases the effect is significant. Indeed, unless γ is very small and the demand function close to vertical (e.g. $\gamma = 0.1$, as shown in Figure 5), the market nearly disappears with $m \geq 100$.[25]

The economics of the result is straightforward. With m large the cumulative royalty is

$$R_m = mr_m \approx (v - c) + \gamma c_\ell > v - c.$$

Hence, eventually the cumulative royalty is higher than consumers' willingness to pay and the quantity demanded falls to zero.

The mirror-image of the fast decrease of the quantity demanded as m increases is that the equilibrium price becomes close to v very fast. How large must be m so that $p \approx v$? Define

$$(\mathcal{V} - \mathcal{P})(m) \equiv \frac{v - p_m}{v - c - mc_\ell} \cdot 100 = \frac{n\gamma}{\theta + n\gamma} \cdot \frac{\gamma}{m + \gamma} \cdot 100. \tag{3.26}$$

This ratio shows $v - p$ with m SEP holders as a fraction of $v - p$ when $p = c + c_\ell$.

Figure 6 plots (3.26) with nine manufacturers ($n = 9$) who compete à la Cournot ($\theta = 1$) in the downstream market.[26] Consider first $\gamma = 1$ —the linear demand function—. As the black line shows, (3.26) falls to 45 with $m = 1$—so 55% of the difference disappears by the exercise of market power of the single SEP holder and double marginalization. Royalty stacking further reduces the ratio: with $m = 10$ it falls to 8.5; with $m = 50$ it falls to 1,8 and with $m = 100$ it falls to 0.9. Hence, with linear demand price will follow v with a modest number of SEP holders. .

Now, as the figure shows, with any demand curve with $\gamma < 1$ royalty stacking will increase the price to v even faster. Indeed, when γ is very small and the demand function close to vertical (e.g. $\gamma = 0, 1$, as shown in Figure 5), the equilibrium price will be close to v even with a single SEP holder. With γ large (e.g. 10 or 50; see Figure 6) the difference between v and p shrinks a little slower as m rises. But as can be seen in Figure 6, the effect is still significant. More important, recall from Figure 5 that when $\gamma > 1$, output shrinks very fast. For example, $m = 10$, the market shrinks to about one-tenth of the size it would have with no patents.

So the implication of the model is that even with a modest number of patent holders, the effect of royalty stacking on output is severe, unless demand is very concave. On the other hand, if demand is very concave, the effect of royalty stacking on output is slower to emerge. But then, even one patent holder would charge a royalty which would make price rise close to v, consumer's maximum willingness to pay. One way or another, royalty stacking is not about marginal effects.

Result 3.11. *Royalty stacking has severe effects on market performance. If demand is not too concave, the market nearly disappears with a modest number of patent holders.*

[25] With γ close to zero the demand curve nearly vertical but concave. Then the equilibrium price is very close to v even with $m = 1$ (see equation (3.22)) and the equilibrium price increases only slowly as SEPs stack. Thus while the equilibrium quantity falls slowly with m, royalty stacking is not very relevant to begin with.

[26] Note that because we fix n, Figure 4 underestimates the effect of an increasing number of SEP holders.

3.4.3. Royalty stacking when new SEP holders add value

So far we have assumed fixed v and c. One may argue, however, that phones have protractedly improved over time with the addition of new functionalities, which have been contributed by a growing number of SEP holders.[27]

To study the effect of quality improvements on royalty stacking, in this section we follow Lerner and Tirole (2004) and assume that $v = \upsilon m$. That is, SEP holders contribute valuable features which linearly increase users' willingness to pay v. We also assume that $c = \zeta m$ —better products are more expensive to manufacture.

Because v and m are a parameters, we can just substitute υm and ζm into (3.21) to obtain the cumulative royalty. When the number of SEP holders is large, this substitution yields

$$\mathcal{R}_m = m r_m = \frac{m^2}{m+\gamma}\left[(\upsilon - \zeta) + \frac{\gamma c_\ell}{m}\right] \approx m(\upsilon - \zeta).$$

So if quality increases linearly in the number of SEP holders, so do cumulative royalties. The economics at work is simple: as Result 3.8 shows, with royalty stacking the cumulative royalty increases dollar by dollar with users' willingness to pay. Furthermore, with m large,

$$p \approx m\upsilon = v;$$

that is eventually the equilibrium price grows *pari passu* with the increase in willingness to pay because SEP holders extract all surplus. Consequently

$$Q_m = S \cdot (m\upsilon - p)^\gamma = 0$$

So:

Result 3.12 (Royalty stacking with SEP holders who add value). *With royalty stacking the cumulative royalty grows without bound prices increase dollar by dollar with willingness to pay and the market eventually disappears.*

4. Evidence from the mobile wireless industry

4.1. Looking for royalty stacking

How can one test whether there is royalty stacking when neither individual nor cumulative royalties are observable?[28] As we have seen, the equilibrium price increases with the number of SEP holders. So, to test the theory one would like to vary the number of SEP holders over time keeping everything else constant and measure the impact of additional SEP holders or SEPs on equilibrium prices. Nevertheless, while the data on the mobile wireless market that we will use below is comprehensive

[27] It is sometimes claimed that the number of SEPs has grown over time because of a proliferation of patents of little value which are used to extract royalties from manufacturers. This view is consistent with a rising m but a stagnant v.

[28] Although some estimates of aggregate royalties have been suggested, they vary widely.

and includes nearly all worldwide sales of wireless phones and their average selling price since 1992, we do not have data to keep "everything else"—costs, quality, willingness to pay, incomes, substitute prices, the downstream intensity of price competition—constant.

Because of this, we will exploit the fact that, as we showed in section 3.4.2, royalty stacking theory predicts that output will fall fast as the number of SEP holders increases; and prices will quickly rise close to v, even with a relatively modest number of patent holders. At the same time, with severe royalty stacking the industry concentrates and margins fall.

A potential problem with this strategy is that exogenous factors, such as exceptional technological opportunity, or falling manufacturing margins forced by competition, may compensate for royalty stacking, masking its effect in the data. Nevertheless, this is inconsistent with the mechanics of royalty stacking because it assumes that patent owners keep their royalty fixed when surplus increases for an exogenous reason. But if surplus increases for whatever reason, then the patent holders will raise the royalty rate and they will do it dollar-by-dollar.

To see this, recall that in the long-run equilibrium

$$v - p = \frac{n^*(m)\gamma}{\theta + n^*(m)\gamma} \cdot \frac{\gamma}{m + \gamma} \cdot (v - c - mc_\ell),$$

where $n^*(m)$ denotes that the equilibrium number of manufacturers is a function of the cumulative royalty $\mathcal{R}_m$. Moreover, we saw in section 3.3 that $\frac{dn^*(m)}{dm} < 0$. Therefore, with severe royalty stacking

$$v - p \approx 0$$

and, consequently, $p \approx v$. So with severe royalty stacking, prices grow dollar by dollar with v. One implication is that a quality improvement, which increases willingness to pay, raises the equilibrium price dollar-by-dollar. Similarly, as Result 3.8 shows, any change in cost c is compensated by a change with opposite sign of the royalty rate $\mathcal{R}_m$ and does not affect price, and so are changes in γ and θ. Thus, the endogeneity of the royalty rate under severe royalty stacking implies that the effect of royalty stacking cannot be undone by "other factors"; on the contrary, as m increases, quantity must fall, prices must increase, and concentration must rise.

In what follows we study the observed evolution of prices, quantities and structure in the world mobile wireless manufacturing industry —firms that manufacture phones and tablets—between 1992 and 2013. We also examine the evolution of gross margins of the firms that participate in the 3GPP SSO, distinguishing between SEP holders and the rest of the firms.

4.2. Prices and quantities

For data on prices and quantities, we rely on Strategy Analytics —a large industry analysis firm that tracks different parts of the industry for market analysis. Strategy analytics tracks device sales by

Figure 7 shows the evolution of worldwide phone device sales in millions since 1994, distinguishing by technological generation (1G, 2G, 2GPRS, 2.5G, 2.5 GPRS, 3G, 3.5G and 4G); it also shows the number of essential patent holders. Now as can be seen in Figure 7, between 1994 and

2013 the number of essential patent holders grew from 2 to 130. Royalty staking theory predicts that sales of phones should have declined or (if quality increases demand) at least stagnated. By contrast, device sales have grown very fast. As can (barely) be seen in Figure 7, in 1994 the one manufacturer (Ericsson) sold 29 million devices. In 2013, by contrast, 43 manufacturers sold 1,810 million devices, a 62-fold increase, at an average rate of 24% per year. Moreover, if anything, successive generations of phones sell more devices than older ones. For example, manufacturers sold 782 million 3.5 G phones in 2013, the seventh year of existence of that generation. This is the largest number of phones sold in one year of any given generation .

Device sales have grown because prices have fallen and quality has increased. The weighted worldwide average selling price of a device (measured in 2013 dollars) fell to one-fifth of its initial level, from \$853 in 1994 (when only 1G and 2G phones were available) to \$173 in 2013, or -8.7% per year on average. Yet, the fast and accelerating introduction of devices of the latest technological generation, which sell for higher prices, masks that quality-adjusted prices are falling considerably faster.

A rough way to gauge the rate of fall of quality-adjusted prices is to track the average selling price of each technological generation, which we do in Figure 8[29]. As can be seen in the figure, the introductory price has fallen with each successive generation, despite of the fact that over time quality has improved. By contrast, royalty stacking theory predicts that the introductory price of a device should increase with quality, as patent holders go after consumer surplus. And the effect should worsen over time as the number of SEP holders is increasing over time.

Figure 8 also shows that the average selling price falls fast within each generation. To compute the average rate of fall of each generation, we run a simple pooled OLS regression with dummies for each technological generation, viz.

$$\ln p_{i,t_i} = \alpha_1 + \alpha_i \sum D_i + \beta_1 t_1 + \beta_i \sum D_i t_i,$$

where $i \in \{$2G,2G(GPRS),2.5G,2.5G(GPRS),2.75G, 3G,3.5G,4G,$\}$, t_i is the number of years between the current year and the year of introduction of generation i, D_i is a dummy variable that identifies technological generation i, and t_i is the number of years after generation i was introduced. Table 1 reports the results.

Columns 1 to 4 report the regression results in logs. Column 5 shows the price predicted by the regression during the first year of the respective generation and column 6 shows the average rate of fall of change of each generation's price. Note that the average annual rate of change ranges from -11.4% for 3.5G devices to -24.8% for 2.5 G (GPRS). Again, this contradicts the prediction of the theory.[30]

[29] This is a simple variant of hedonic prices, to the extent that characteristics in the phones of a given generation remain constant over time. Because the devices of a given generation tend to improve over time, this probably underestimates the rate of fall of quality-adjusted prices. See, for example, Triplett (1996).

[30] Prices are higher at the introduction date if manufacturers who introduce the next generation enjoy market power, which is eroded over time. As we saw, however, with severe royalty stacking, however, downstream market power is not quantitatively very relevant.—can be at most equivalent to one more patent holder.

4.3. Market structure

Royalty stacking theory also predicts that the industry will concentrate as the number of SEP holders rises. Figure 9 shows the number of phone manufacturers between 1992 and 2013 and average sales per manufacturer. Note that the number of firms steadily grew from one in 1994 (Ericsson) to 20 in 2002, then jumped to 40 in 2006 and then stabilized. With the exception of the initial years of the industry, average sales per firm have hovered around $5-7 billion. This shows that as industry size grows, new manufacturers enter.[31]

Firms have different sizes and the number of manufacturers might not depict concentration and structure accurately. We have data on the number of devices sold by each manufacturer since 2001 and Figure 10 plots the number of equivalent device manufacturers[32]. Note that it hovers around six until 2004, then falls to about five in 2008 and then steadily grows up to about nine in 2013. Hence, concentration fell, despite of the fact that sales per equivalent manufacturer more or less doubled, from about $20 billion between 2001 and 2003 to about $40 billion since then. Again, we fail to find evidence consistent with royalty stacking theory.

4.4. Margins

4.4.1. The evolution of gross margins

As we saw in the previous section if patent holders add no value, SEP holders' and manufacturer's Lerner margins should fall with royalty stacking. By contrast, if patent holders add value, their Lerner margins may remain constant, but manufacturers' margins still fall .

To examine whether there is some trace of royalty stacking in margins, we collected financial data on the universe of firms that participated in the development of the global third and fourth generation wireless cellular standards—over 300 firms— between 1994 and 2013 and for each computed gross margins year by year.[33,34] We coded each firm by the number of SEPs it can assert and separated the sample between firms who held at least one SEP and firms who hold no SEP (until a firm declares its first SEP, it is classified as non-SEP holder).

Figure 11 shows gross margins of SEP holders and the rest of participants in 3GPP for which we could find financial data (right axis). The average gross margin of SEP holders hovers between 30% and 35%, but shows no downward trend. The average gross margin of non-SEP holders is higher and fluctuates more, but there is no sustained, long-run trend.

[31] In Appendix B we describe the data.

[32] The Herfindahl index is usually measured with sales, but we do not have firm-level sales.

[33] Gross margin is calculated as the ratio of revenues less the cost of goods sold (production or acquisition costs) to sales. It is an imperfect measure of Lerner margins because it includes fixed, average costs and Ricardian rent. An additional limitation might be that some of the cost items included in production or acquisition costs are not part of short-run marginal costs. This is less important here because we track the long-run performance of the industry. Then long-run marginal cost, which includes costs which are fixed in the short run, are relevant for pricing decisions. See Boiteaux (1960).

[34] Gross margins are obtained from Thomson One. Each year each firm's gross profit is divided by total revenues as reported on the firm's financial statements.

Figure 12 repeats the exercise, but only with device manufacturers. Now the average gross margin of SEP holders hovers around 30% , but shows no trend. And again, the average gross margin of non-SEP holders is higher and fluctuates more, but there is no sustained, long-run trend.

We checked the robustness of these trends by classifying as "SEP holder" a firm with at least 100 SEPs; by distinguishing between members of the SSO and attendees; by trying with an alternative financial database with coverage since 2004, but with data from more firms; and by using weighted averages. While levels may vary a bit, no trend appears.

In addition, we checked the robustness of these trends by classifying as "SEP holder" a firm with at least 100 SEPs; by distinguishing between members of the SSO and attendees; by estimating the same model with a different financial database with coverage since 2004, but with more firms; and by using weighted averages. While levels may vary a bit, no trend appears.

4.4.2. Regression analysis

Many other factors affect firms' gross margins. To control for them we also run the following regression:

$$\begin{aligned}
\text{gross margins} \quad = \quad & \alpha_0 + \alpha_1(\text{cumulative \# of SEP holders}) + \alpha_2(\text{SEP holder dummy}) \\
& +\alpha_3(\text{SEP holder dummy } \times \text{cumulative \# of SEP holders}) \\
& +\beta_1(\text{R\&D intensity}) + \beta_2(\text{total \# of employees}) + \beta_3(\text{capital stock}) \\
& +\gamma_1(\text{component f.e.}) + \gamma_2(\text{device f.e.}) + \gamma_3(\text{other f.e.}) \\
& +\delta_1(\text{country f.e.}) \\
& +\xi_1(\text{component f.e } \times \text{\# of SEP holders}) + \xi_2(\text{ device f.e. } \times \text{\# of SEP holders}) \\
& +\xi_3(\text{other f.e. } \times \text{\# of SEP holders})
\end{aligned} \tag{4.1}$$

The first coefficient, α_1, measures the effect on margins of the cumulative number of SEP holders. The second coefficient, α_2, measures whether SEP holders have systematically different margins. The third coefficient, α_3, measures whether the number of SEP holders has a systematic differential effect on SEP-holders' margins.

We also control for other determinants of gross margins. First, firm-specific characteristics: R&D intensity (β_1), the number of employees (β_2) and the size of the capital stock (β_3). Second, the firm's place in the value chain (see Figure 3): the base category is infrastructure manufacturer and we add dummies for a component manufacturer (γ_1), a device manufacturer (γ_2) and other non-manufacturer (γ_3). Third, a fixed effect controlling for the country where the firm's headquarter is located (δ_1). Last, we add interaction terms between he firm's place in the value chain and the number of SEP holders (ξ_i).

If additional patent holders add no value, as some in the literature have argued, the model predicts that margins should fall as the number of SEP holders rises. On the one hand, as the number of SEP holder rises, each individual SEP holder prices less aggressively and gross margins should fall. On the other hand, manufacturers' margins should fall as royalty stacking increases royalties. So $\alpha_1 < 0$. Moreover, the interaction coefficient, α_3, may be positive or negative, but in any case $\alpha_1 + \alpha_3 < 0$. If, on the other hand, patent holders add value, then the model still predicts that manufacturers' margins should fall, so $\alpha_1 < 0$. But now the interaction term, α_3, may be positive and $\alpha_1 + \alpha_3$ may be positive or zero.

Table 2 shows the results of six regressions, starting with a baseline with only the number of SEP holders (α_1) and a dummy variable for SEP holders (α_2). Then we progressively add firm-characteristics (regression 2); dummies to distinguish the firm's place in the value chain (regression 3); country dummies (regression 4); and interaction terms (regressions 6 and 7).

The first regression shows that SEP holders have smaller margins. Moreover, there is no relationship between the number of SEP holders and margins, for the coefficient is insignificant at the 10% level and minuscule: an additional 100 SEP holders decreases margins by 0.05 percentage points. More important, the regression's R^2 is 0.02. Royalty stacking theory, by contrast, predicts that the effect of additional SEP holders on margins will be overwhelming.

Of course, R^2s grow as we progressively add variables: to 0.06 when we add firm-characteristics (regression 2); to 0.12 when we add dummies to distinguish the firm's place in the value chain (regression 3); and to 0.32 when we add country dummies (regression 4). By contrast the regressions' R^2 do not change with interaction terms which depend on the number of SEP holders (regressions 6 and 7). I other words, firm characteristics, the place of the firm in the value chain and, especially, the country where the firm is located, explain about one-third of the variation in margins. By contrast, the number of SEP holders shows no relationship with margins. This is inconsistent with royalty stacking theory.

We can confirm this conclusion by looking at Column 6 in Table 2, which shows the regression with all controls added . Note first that the effect on gross margins of additional SEP holders is insignificant and in any case slightly positive: increasing the number of SEP holders from 0 to 100 increases gross margins in 2.5 percentage points. Second, the interaction coefficient between the SEP holder dummy and the cumulative number of SEP holders is significant at the 10% level, but positive. If the number of SEP holders increases from 0 to 100, SEP holders' gross margins increase by 6.6 percentage points. While the 95% confidence interval is rather wide (if the number of SEP holders increases from 0 to 100, the size of the effect ranges from -1 percentage points to 14.6 percentage points), the direction of the change is the opposite to that predicted by the royalty stacking hypothesis when patents are worthless. Moreover, a positive relationship between SEP-holders' margins and the number of SEP holders is possible with royalty stacking, but only if each adds

Last, like SEP holders, device manufacturers' gross margins seem to be systematically lower than the baseline group (infrastructure manufacturers). Nevertheless, the number of SEP holders does not seem to affect them: the interaction coefficient is statistically insignificant and, in any case, it is small: the point-estimate of the effect on gross margins of increasing the number of SEP holders from 0 to 100 is 2.59 percentage points. So the regression fails to detect any negative effect of the number of patent holders on margins. Again, this is inconsistent with royalty stacking theory.

Table 3 repeats the estimation, but now the explanatory variable is the number of SEPs (in thousands). With a few exceptions, the point estimates are similar. Again, the effect on gross margins of SEPs is positive but insignificant and small: increasing the number of SEPs from 0 to 100,000 would increase gross margins by 2.4 percentage points. And the interaction coefficient between the SEP holder dummy and the cumulative number of SEP holders is statistically insignificant and positive.

4.4.3. Endogeneity concerns

Our regressions cannot rule out that the number of SEP holders is endogenous to margins. If royalty stacking, working through the number of SEP holders, affects margins and more broadly, market performance, then patenting and the number of SEP holders are jointly determined. To address endogeneity, one would have to find an exogenous and unanticipated shock that either increases or decreases the number of SEP holders. This is hard. So one may wonder what is the sign of the bias of the SEP variable in a regression like (4.1) if such reverse causality is present.

Performance variables affect patenting behavior and the number of SEP holders. If royalty stacking is occurring, there should be less innovation and patenting, because the market shrinks, and this moderates the measured negative effect on margins of royalty stacking. So in a regression like (4.1), the absolute size of the coefficient of the number of SEP holders, α_1, would be biased downwards in absolute value. Nevertheless, even if biased, the coefficient will be negative in the presence of severe royalty stacking. The reverse causality cannot fully compensate the negative effect of royalty stacking on margins, because then performance would improve and that would prompt more patenting, not less.

5. Conclusion

In complex technologies such as the high-tech industry, where most products sold to end users incorporate many patented inputs, some authors have used the Cournot-complements logic to suggest that royalties might be too high. Market-driven mechanisms, such as cross-licensing and reputation effects might not suffice to prevent royalty stacking. Indeed, number of proposals have been put forth to solve the perceived problem, all aimed at lowering royalties charged by patent holders. These include patent pool rates (Lerner and Tirole [2004]), valuation of technologies before they are adopted as the standard (Swanson and Baumol [2005], Skitol [2005]) or capping royalties based on the incremental value of the patents over their next best alternatives (Farrell et al. [2007]).

In this paper, we developed an equilibrium model that describes the mechanisms with which royalty stacking may occur and derived the observable implications of the hypothesis. According to the literature and the model, when the number of SEP holders steadily grows over many years, royalty stacking is a protracted force which will, sooner or later, become the overwhelming determinant of industry performance.

We have shown that in the mobile wireless industry prices have fallen, quantities have grown and the industry has become less concentrated over time. Royalty stacking theory predicts the opposite: prices rise, quantities fall, the industry concentrates. Similarly, royalty stacking theory predicts falling Lerner margins; the data by contrast, shows no relationship between margins and the number of SEP holders. And, moreover, while royalty stacking predicts that the industry should nearly collapse, chocked by high prices which rise any time a valuable innovation is introduced, the data, by contrast, shows a thriving industry.

It is sometimes argued that this does not prove that royalties do not stack, because “it could have been even better”: prices could have fallen even faster and output could have increased even more. Nevertheless, this claim ignores that with royalty stacking the cumulative royalty charged by SEP holders is endogenous. and favorable cost shocks or quality increases are appropriated by SEP holders. For this reason, prices must rise with the number of SEP holders. So, with royalty stacking prices would have risen and, therefore, prices could not have fallen “even faster” (it could *not* have been better).

So, no matter how we look at the data, we fail to reject the null hypothesis of no royalty stacking.

Appendix

A. Some technical results

A.1. Royalty stacking with unbounded willingness to pay

A.1.1. Demand

Consider demand function (3.5) in the text

$$Q = S(v + p)^{\gamma},$$

with $\gamma < 0$ and $v \in \mathrm{IR}$. When $v < 0$ the quantity demanded approaches infinity as $p \to -v$ and approaches 0 as $p \to \infty$. Thus willingness to pay for the first unit is very high. Now the price elasticity is

$$\eta(p) = -\gamma \frac{p}{v + p}.$$

When $v > 0$, $\eta(0) = 0$, $\eta' > 0$ and $\lim_{p\to\infty} \eta(p) = -\gamma$. On the other hand, if $v < 0$, p is bounded below by $-v$, $\lim_{p\to -v} \eta(p) = \infty$, $\eta'(p) < 0$ and $\lim_{p\to\infty} \eta(p) = -\gamma$. Last, when $v = 0$ this yields the constant-elasticity demand with $\eta = -\gamma$.

A.1.2. Downstream equilibrium

Again, we begin with the last stage of the game. Manufacturers take n and $\mathcal{R}$ as given and each solves

$$\max_{q_i} \left\{ q_i \left[P(Q) - (c + \mathcal{R}) \right] \right\}.$$

Standard manipulations of the first order condition (3.6) yields that in a symmetric equilibrium

$$Q = S \left(\frac{n\gamma}{\theta + n\gamma} \right)^{\gamma} (v + c + \mathcal{R})^{\gamma} \tag{A.1}$$

and

$$p = \frac{-\theta v + n\gamma(c + \mathcal{R})}{\theta + n\gamma}. \tag{A.2}$$

Note that the rate of pass through is

$$\frac{\partial p}{\partial \mathcal{R}} = \frac{n\gamma}{\theta + n\gamma}.$$

Consider first $v \geq 0$. Because $n\gamma < 0$, a necessary condition for existence of an equilibrium with production is $\theta + n\gamma < 0$; otherwise $\frac{n\gamma}{\theta + n\gamma} < 0$ and $Q < 0$ in (3.10).[35] Now if $v < 0$ but $v + c + \mathcal{R} \geq 0$, again $\theta + n\gamma < 0$ is necessary for existence.

Last, if $v < 0$ but $v + c + \mathcal{R} < 0$, then $n\gamma \cdot (v + c + \mathcal{R}) > 0$ and $\theta + n\gamma > 0$ is necessary for existence of an equilibrium with production. Nevertheless, then $\frac{\partial p}{\partial \mathcal{R}} = \frac{\partial p}{\partial c} = \frac{n\gamma}{\theta + n\gamma} < 0$: higher costs *reduce* the equilibrium price—the rate of pass through is negative—, a rather implausible consequence. For this reason, we ignore this case and henceforth assume that $v + c + \mathcal{R} > 0$ and $\theta + n\gamma < 0$.

A.1.3. Royalty stacking

Assume that demand is of the form (3.5) and let each SEP holder choose r to

$$\max_{r} \left\{ (r - c_\ell) \times \frac{S}{(v + p)^{-\gamma}} \right\}.$$

Some algebra yields that

$$r_m = \frac{v - c - \gamma c_\ell}{(-\gamma - m)}$$

[35] Note that with $\theta = n$ (monopoly conjectures) this condition reduces to $1 + \gamma < 0$; that is, the upper bound of the elasticity must be greater than one.

and

$$\mathcal{R}_m = \frac{m}{(-\gamma - m)}(v - c - \gamma c_\ell),$$

with $m + \gamma < 0$. Thus for fixed γ,

$$\lim_{m \to -\gamma} r_m = \lim_{m \to -\gamma} \mathcal{R}_m = \infty.$$

Now the elasticity tends to $-\gamma$ as p rises. It follows that unless $-\gamma$ is very large, an equilibrium with production does not exist. For example, in 2013 there were 130 different SEP holders. Hence $-\gamma < 130$ implies that the industry should have disappeared.

A.1.4. Can royalty stacking increase downstream profits?

One of the predictions of the model in section 3 is that concentration rises with the cumulative royalty. The economics at work is that with fixed n, higher royalties reduce industry and per-firm profits

$$[p - (c + \mathcal{R})]\, \frac{Q}{n},$$

which now are not enough to pay for the entry cost σ unless concentration rises. Nevertheless, it is well known that oligopolists' profits may rise when costs increase (see, for example, Seade (1985) and Kimmel (1992)). If profits increase with $\mathcal{R}$ and fixed n then concentration would fall with higher royalties.

Under which circumstances will profits rise? With demand function (3.5) total profits are

$$-\frac{\theta[v + (c + \mathcal{R})]}{\theta + n\gamma} S(v + p)^{\gamma}.$$

With fixed n

$$\frac{\partial \pi}{\partial \mathcal{R}} \propto (v + p)^{\gamma} + [v + (c + \mathcal{R})](v + p)^{\gamma - 1} \frac{\partial p}{\partial \mathcal{R}}.$$

Now recall that $\frac{\partial p}{\partial \mathcal{R}} = \frac{n\gamma}{\theta + n\gamma}$. Hence

$$\frac{\partial \pi}{\partial \mathcal{R}} \propto 1 + \frac{v + (c + \mathcal{R})}{(v + p)}^{\gamma - 1} \frac{n\gamma}{\theta + n\gamma}.$$

Substituting (A.2) into this expression, simplifying and rearranging yields

$$\frac{\partial \pi}{\partial \mathcal{R}} \propto 1 + \gamma.$$

Hence profits rise with $\mathcal{R}$ only if $-\gamma \in [0, 1)$. Now γ is the upper bound of the price elasticity. But if $-\gamma \in [0, 1)$, an equilibrium with production does not exist. Hence, rising profits are inconsistent with royalty stacking; concentration must increase with $\mathcal{R}$ if an equilibrium with royalty stacking and production exists.

A.1.5. Royalty stacking and increasing SEP margins

In the text we obtained that SEP holders price less aggressively as m increases. Thus r_m, μ_m and $\mathcal{L}_m$ are decreasing in m. If willingness to pay is unbounded, these results reverse as $Q \to 0$. Then r_m, μ_m and $\mathcal{L}_m$ are increasing in m.

To see this, recall that

$$r_m = \frac{v - c - \gamma c_\ell}{(-\gamma - m)},$$

$$\mu_m \equiv r_m - c_\ell = \frac{v + c + m c_\ell}{(-\gamma - m)}$$

and

$$\mathcal{L}_m \equiv \frac{r_m - c_\ell}{r_m} = \frac{v + c + m c_\ell}{v + c - \gamma c_\ell}.$$

Hence

$$\frac{\partial r_m}{\partial m} = \frac{v - c - \gamma c_\ell}{(-\gamma - m)^2} > 0;$$

$$\frac{\partial r_m}{\partial m} = \frac{c_\ell}{(-\gamma - m)} + \frac{v + c + m c_\ell}{(-\gamma - m)^2} > 0,$$

and

$$\frac{\partial \mathcal{L}_m}{\partial m} = \frac{c_\ell}{v + c - \gamma c_\ell} > 0.$$

Nevertheless, increasing individual royalties and margins require $m < -\gamma$ which, we have seen, is unlikely if an equilibrium with royalty stacking and production exists.

A.2. The marginal surplus function

In the text use the marginal surplus function

$$\text{ms} \equiv -P'Q = \frac{p}{\eta} = -\frac{D}{D'};$$

and its derivative with respect to p:

$$\frac{d\text{ms}}{dp}(p) = \frac{1}{\eta(p)}\left[1 - \text{ms}(p)\cdot\eta'(p)\right] = \begin{cases} -\frac{1}{\gamma} & < 0 \quad \gamma > 0, b = 1 \text{ and } v > 0. \\ 0 & \quad \gamma, v \to \infty, \frac{\gamma}{v} \text{ constant;} \\ -\frac{1}{\gamma} & > 0 \quad \gamma < 0, b = -1 \text{ and } v \in \mathrm{IR}. \end{cases}.$$

Note that marginal surplus falls with price if $\gamma > 0$; is constant with exponential demand; and increases with price if $\gamma < 0$.

It is also useful to define the inverse elasticity of the marginal surplus function:

$$\frac{1}{\epsilon_{\text{ms}}} \equiv \frac{Q \cdot \text{ms}'}{\text{ms}} = -\frac{1}{\eta^2}\left[1 + \frac{d\eta}{dQ}Q\right] = \begin{cases} \frac{1}{\gamma} & > 0 \quad \gamma > 0, b = 1 \text{ and } v > 0. \\ 0 & \quad \gamma, v \to \infty, \frac{\gamma}{v} \text{ constant;} \\ \frac{1}{\gamma} & < 0 \quad \gamma < 0, b = -1 \text{ and } v \in \mathrm{IR}. \end{cases}.$$

In what follows the rate of pass through, $\frac{dP}{d(c+\mathcal{R})}$, is of some importance. Within the class of functions as in (3.1), the rate of pass through is constant when marginal cost is flat and the conduct parameter θ is constant[36]. To see this, totally differentiate both sides of (3.6), which yields

$$d(c + \mathcal{R}) = \left(1 - \frac{\theta}{n}\text{ms}'\frac{dQ}{dp}\right)dP = \left(1 + \frac{\theta}{n\epsilon_{\text{ms}}}\right),$$

Hence

$$\frac{dP}{d(c + \mathcal{R})} = \frac{1}{1 + \frac{\theta}{n\epsilon_{\text{ms}}}}$$

and

$$\frac{dP}{d(c + \mathcal{R})} = \begin{cases} \frac{n\gamma}{n\gamma+\theta} & \leq 1 \quad \gamma > 0, b = 1 \text{ and } v > 0. \\ 1 & \quad \gamma, v \to \infty, \frac{\gamma}{v} \text{ constant;} \\ \frac{n\gamma}{n\gamma+\theta} & \geq 1 \quad \gamma < 0, b = -1 \text{ and } v \in \mathrm{IR}. \end{cases}.$$

B. Data description

B.1. SEPs and SEP owners

We use patent declaration data collected from the European Telecommunications Standards Institute (ETSI), spanning 1994-2013, for 3G and 4G wireless cellular standards. The IPR policies of the SSOs forming 3GPP require firms to declare their patents that may be potentially essential to the 3GPP standards (often termed as standards essential patents (SEPs)), and most firms declare these patents to ETSI, the primary SSO who manages 3GPP.

We perform several clean-up and correction steps on the ETSI patent declaration data, such as: (i) identifying missing patent numbers from some patent declarations; (ii) rolling-up firm names to parent companies, that is, names of declaring entities that are subsidiaries or acquired by a parent firm are listed under the name of the parent firm; (iii) identifying all the patents in the same "family" of those declared. In other words, a firm may declare a patent in one jurisdiction (e.g. a US patent), and then obtain patents for the same invention in other jurisdictions (e.g.: a patent in the European Union, JP patent etc.). Per ETSI's IPR policy, all these patents—called a patent family—are

[36] See Bulow and Pleiderer (1983) and Weyl and Farbinger (2013).

considered potentially essential. Therefore, for all the patents in ETSI declaration database, we expand the set to include the related patent family members in the data-set as well.

The final patent declaration data-set contains the list of patents declared to ETSI and the family members of patents declared to ETSI, along with the firm name and the date of declaration.

B.2. 3GPP firm level data

The data-set for the margin analysis and the regression analysis study is based on firms that participated in 3GPP. To conduct the analysis we rely on a comprehensive data-set on 3GPP built by Baron and Gupta (2015). This includes a historical list of 3GPP members, i.e., the names of organizations that are or were members of 3GPP during the development of wireless cellular standards as well as firms that attended 3GPP meetings from 2000-2014. There is a difference between membership and meeting attendance. Firms that are members have voting rights towards what may or may not enter the standard, but any firm can attend the meetings and follow the progress of the standards being developed. Firms often attend the meetings to develop the human capital required to understand the complex technologies that their products need to implement, rather than to directly contribute their technologies to the standards or participate in the voting process. Therefore, some firms become voluntary members of 3GPP but do not attend any meetings, while some firms do not become members and attend the meetings and thereby participate in the standard setting process. For our purposes, in order to capture the universe of firms that may be generating or implementing the standardized technology, we are interested in both membership and attendance records.

The historical list of 3GPP member firms is available for 2000, 2001, 2013, and 2014, and the firms that attended 3GPP meetings between 2000 and 2014 was obtained from the attendance records of over 825 meetings of 3GPP "working group" meetings, where the different aspects of standards are developed. We then merge these membership and attendance records, remove duplicates, clean for firm names, and rolling-up subsidiaries and acquisitions to parent companies (see Baron and Gupta (2015) for further details). Based on this exercise, we identify 765 unique organizations that were members or attendees of 3GPP. Of these 618 are for-profit organizations, while others were educational institutions, research institutions, other SSOs, or government agencies (e.g. FCC, British Telecom Administration, etc.). Because this study is interested in profit margins of firms, these organizations are not included in the analysis as they do not report financial information or do not have revenues, profits, etc.

We collected financial information of firms from ThomsonOne, which lists financial information for public firms from 1994-2014. We identified financial information 223 firms in ThomsonOne from 1994-2014. For each firm, we also identified whether or not a firm is a SEP holder. Any firm with at least one declared SEP is a SEP holder from the date of its first patent declaration to ETSI. In other words, if a firm first declared an SEP in 2005, it would be considered a SEP holder from 2005 onwards only.

For each firm, we also identified where it lies in the mobile wireless value chain, i.e., whether these firms are component manufacturers, consumer devices manufacturers, infrastructure manufacturers, or other non-manufacturing firms. This categorization is done based on SIC codes, information from Onesource, and by interviewing a number of engineers who attended standards meetings. For example: (i) component manufacturers manufacture semiconductor chips, application processors, memory cards, sensors, screens, or cameras, that form component inputs of mobile devices or network base-stations; (ii) device manufacturers package components into mobile devices such as smartphone and tablets; (iii) infrastructure manufacturers manufacture routers, cellular base stations, servers, etc., through which wireless communication is made possible; (iv) the "other" category includes firms such as network operators who maintain and manage the networks and user subscriptions.

B.3. Market data

We collected information on the prices of devices, the number of devices sold, the type of devices sold and the market share of firms from 1994-2013.

Two data-sources were used to collect this information. Data published by Strategy Analytics was used for the number of devices sold, the average selling price (ASP) of a phone and volume of devices sold from 1994-2013. Strategy Analytics is an industry analyst firm that provides the non-quality-adjusted (retail) prices of devices by year. In addition they publish data on the volume of devices sold by year by firm which is used to calculate market share by company. In addition to implications for volumes and price, the royalty stacking theory has implications related to the diversity of products and product brands offered to consumers. Information on all devices released from 1994-2013 was collected from www.gsmarena.com. This is a publicly available data source which provides information on device manufacturers, its specification and the date the product was released.

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Figure 1
Royalty stacking with constant pass-through, log-concave demand

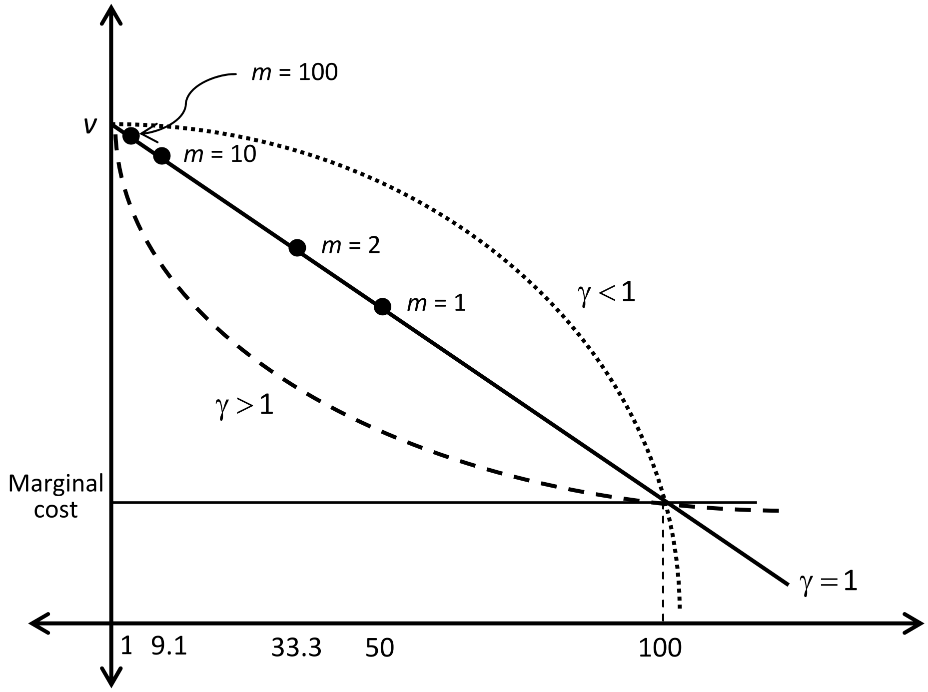


Figure 2
Number of SEPs and SEP holders
(1994-2013)

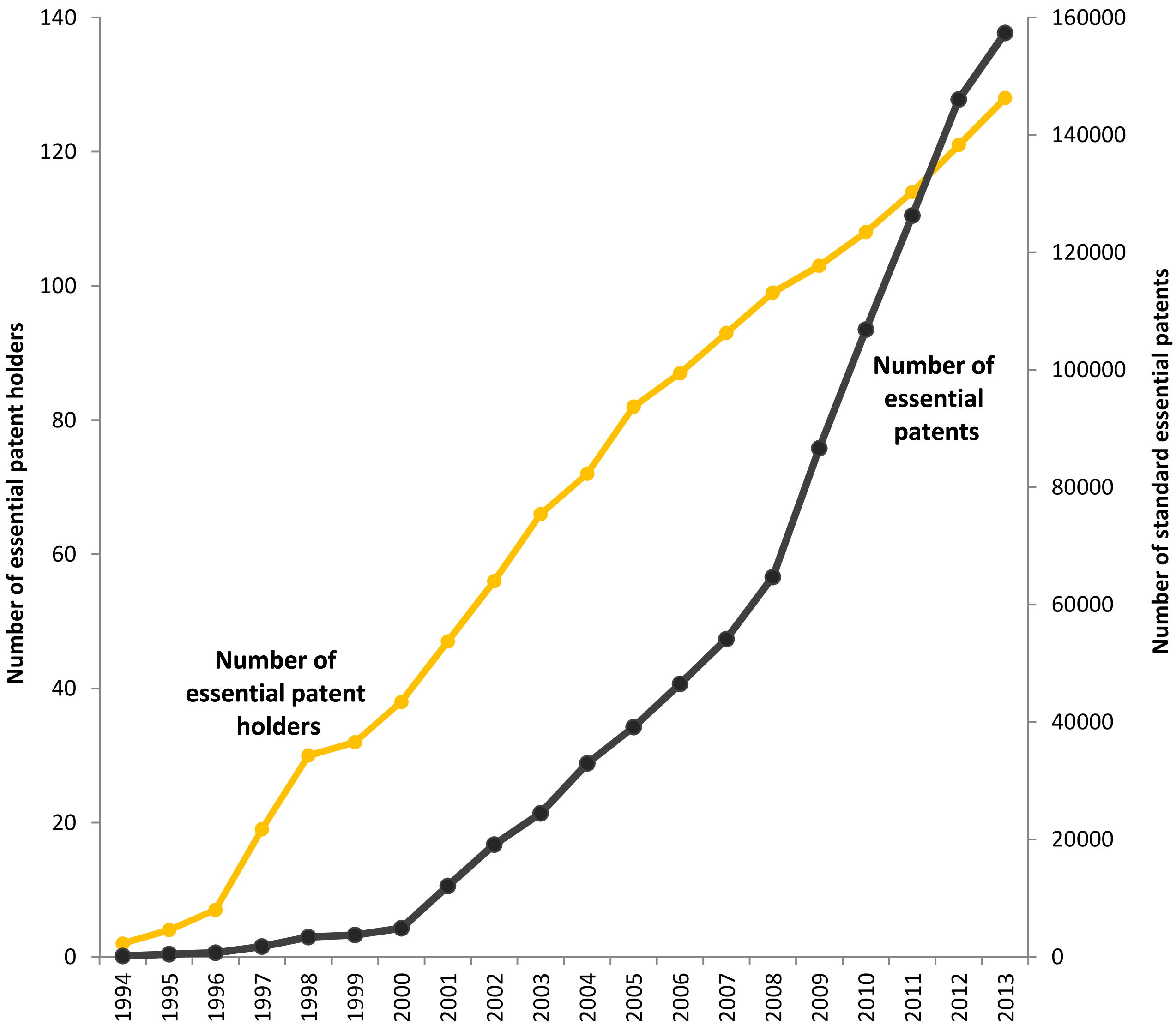


Figure 3

The mobile wireless industry value-chain

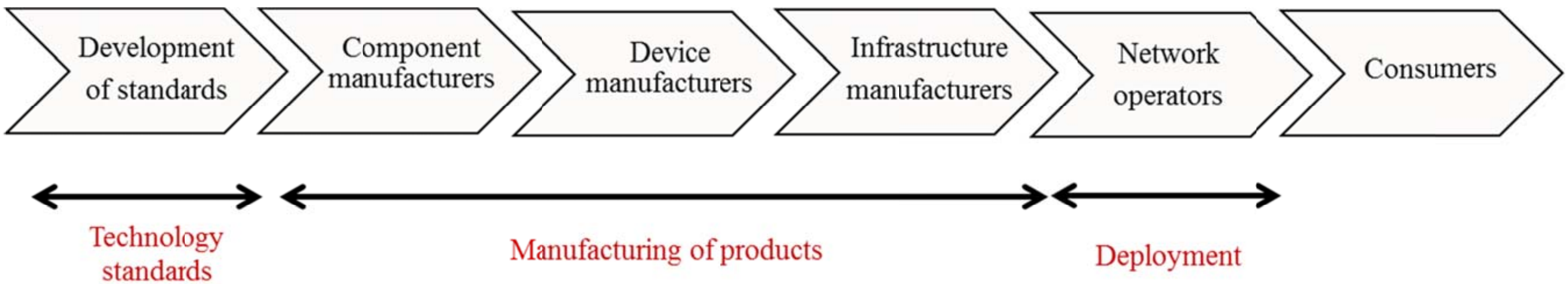


Figure 4: the royalty stacking game

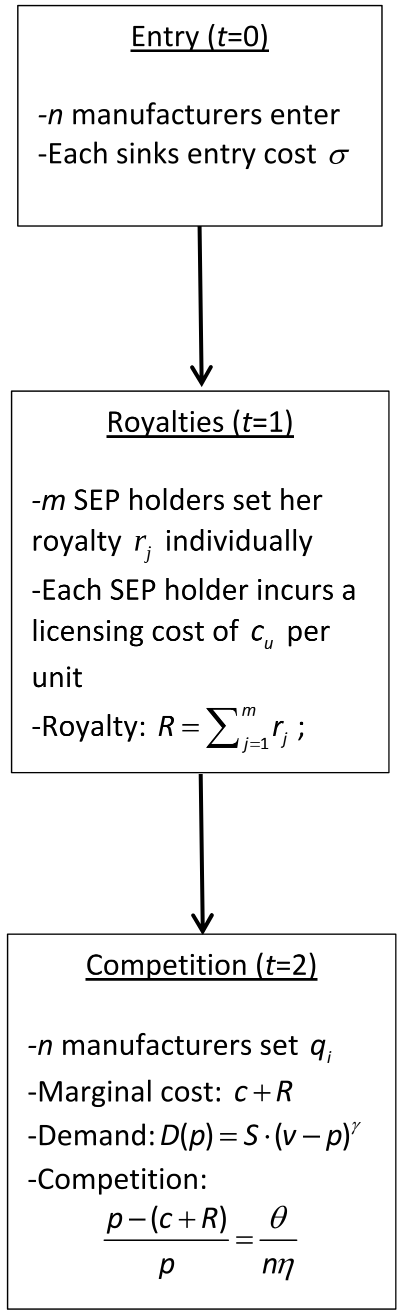


Figure 5
Equilibrium quantity and the number of SEP holders
$100 = Q(c+mc_\ell)$

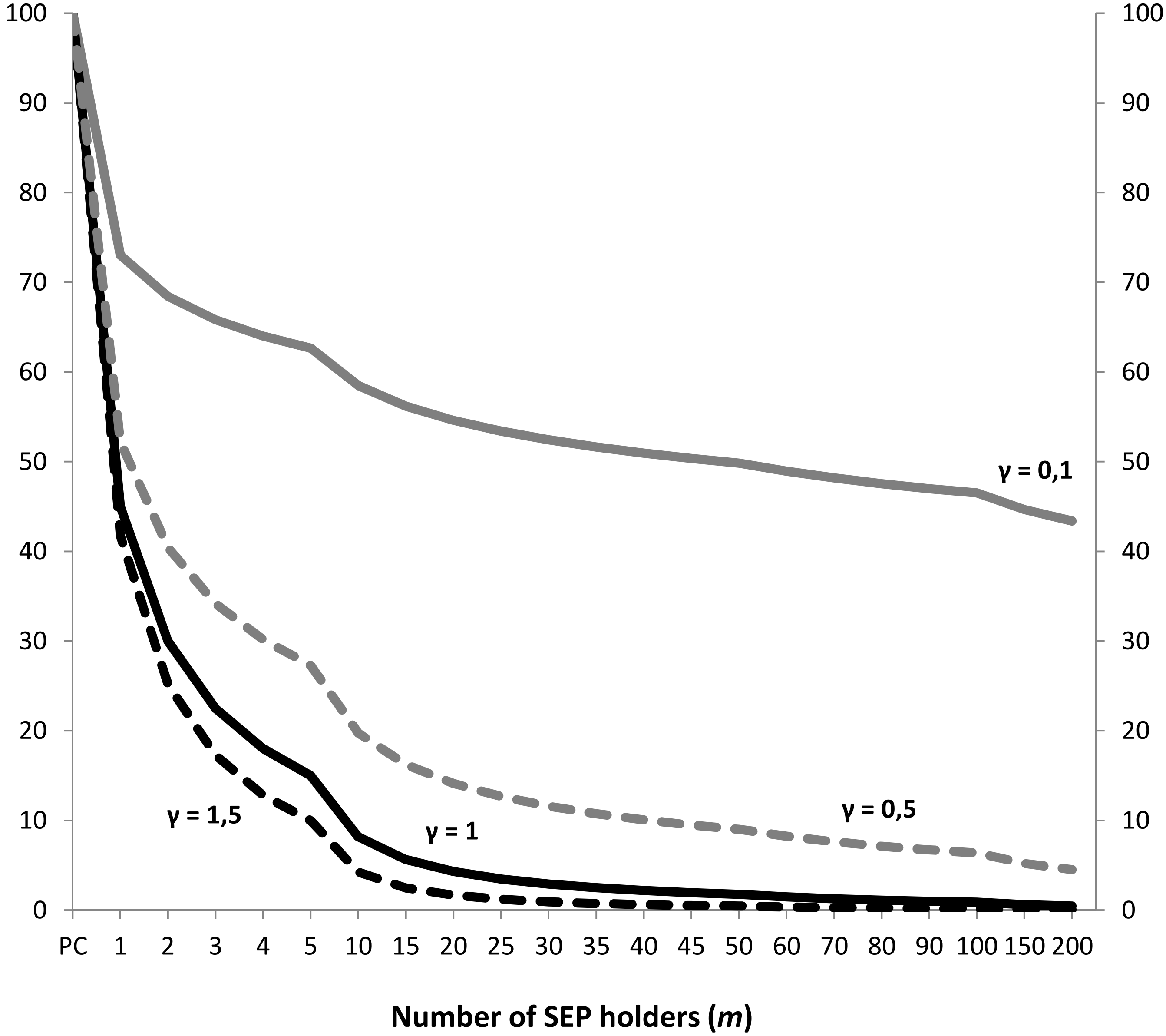


Figure 6
The difference between willingness to pay (v)
and the equilibrium price (p)
100: $v - p = v - (c+mc_\ell)$

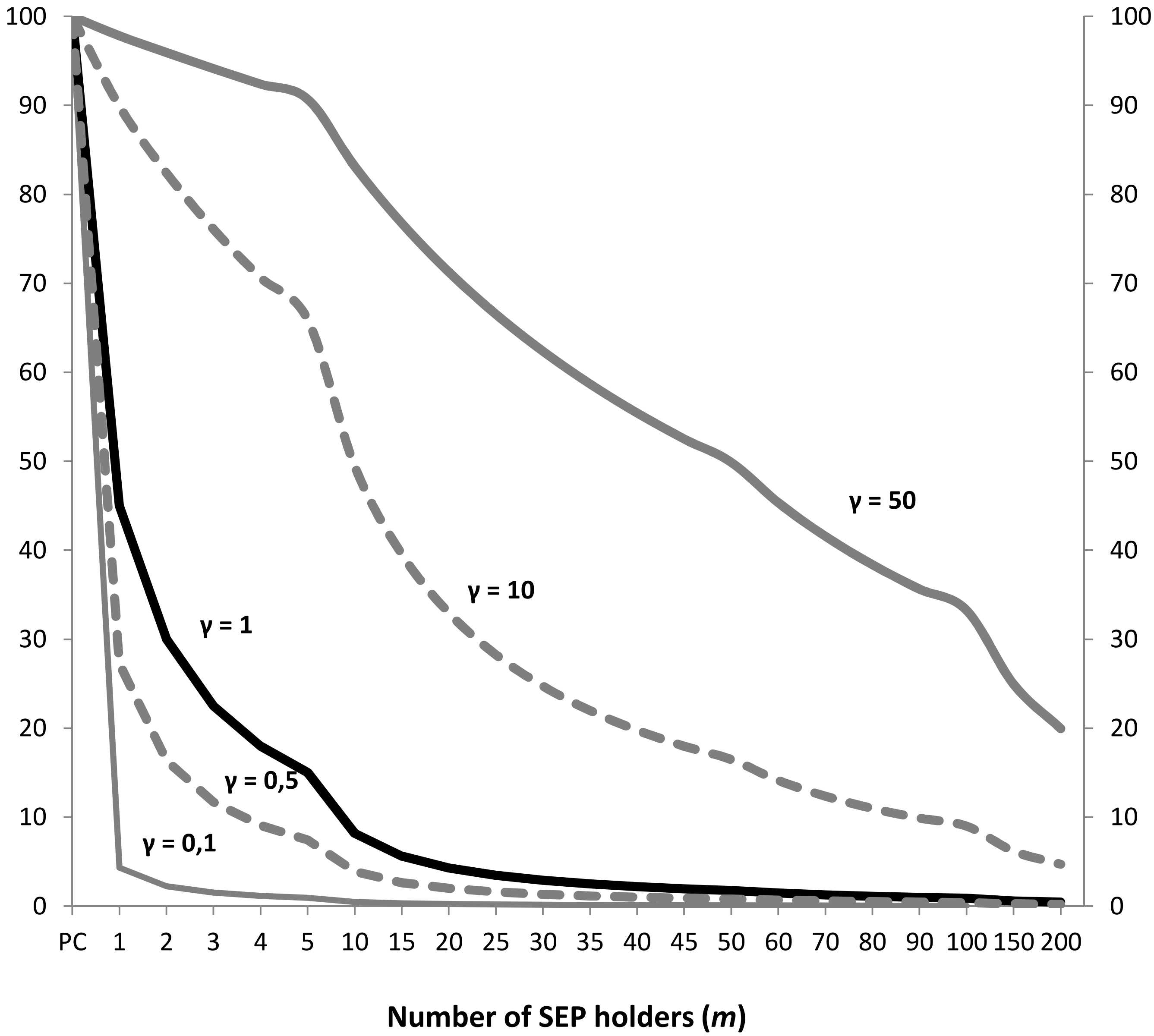


Figure 7
Annual worldwide sales of devices by technological generation, 1983-2013

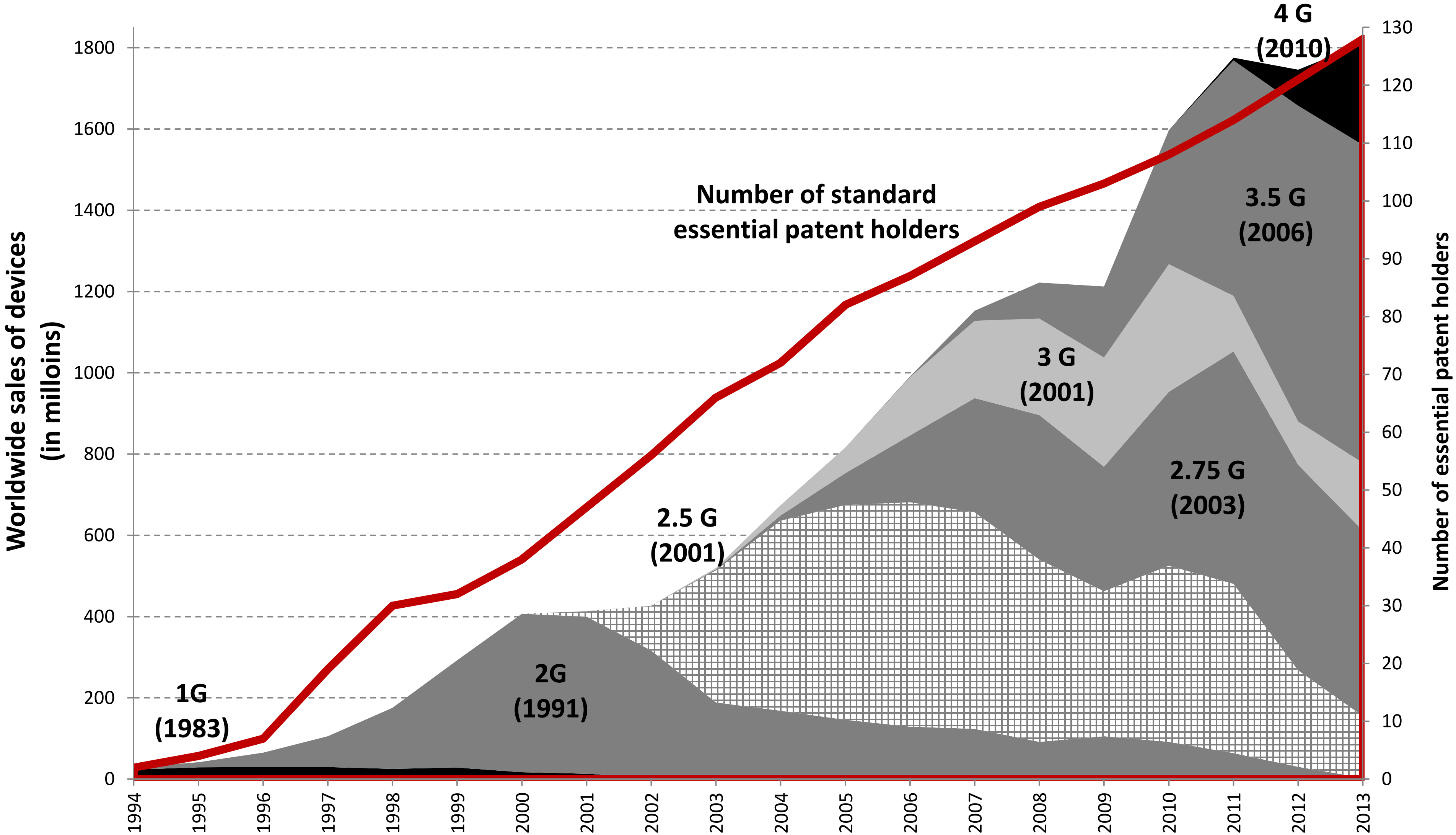


Figure 8
Average selling price of devices and number of SEP holders

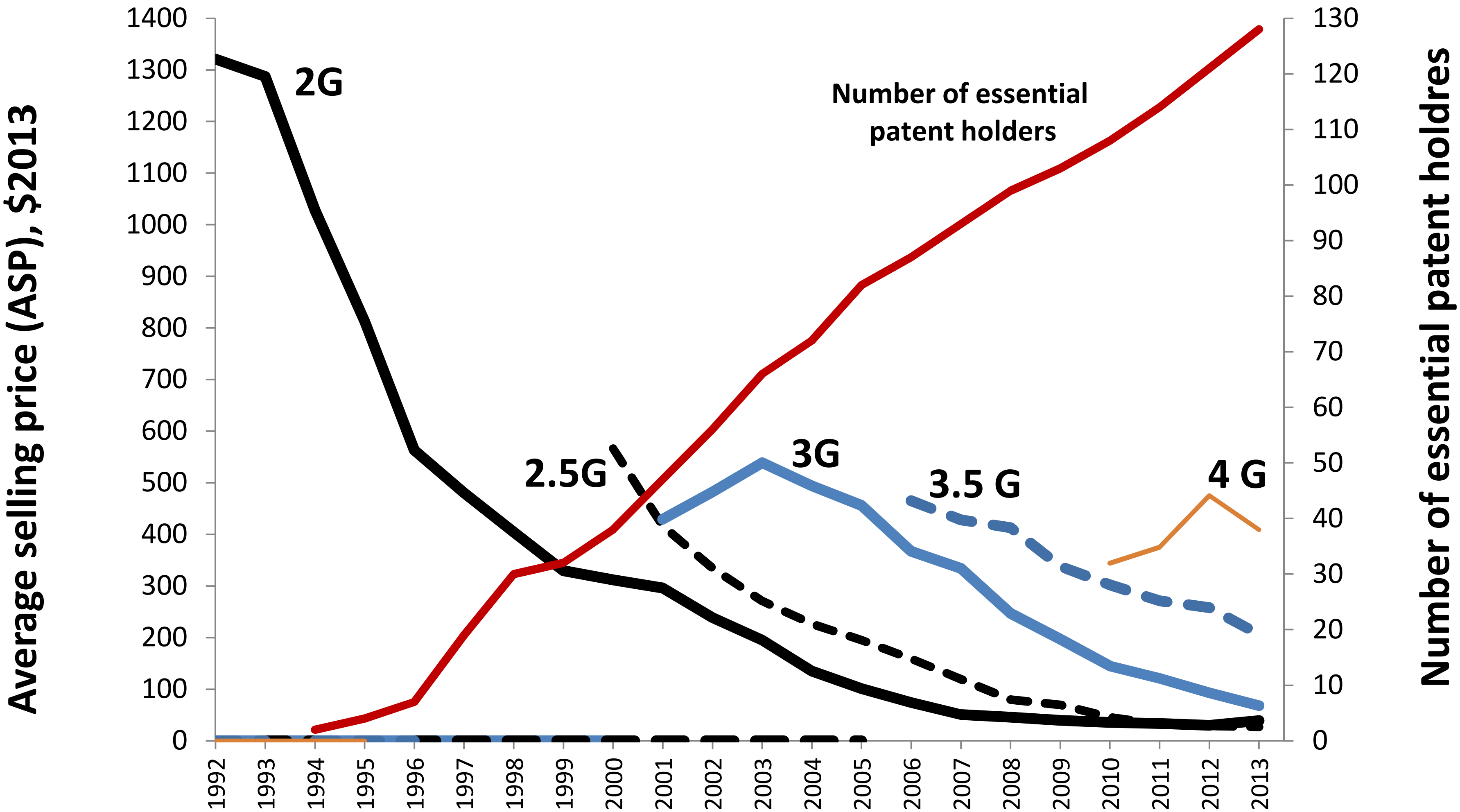
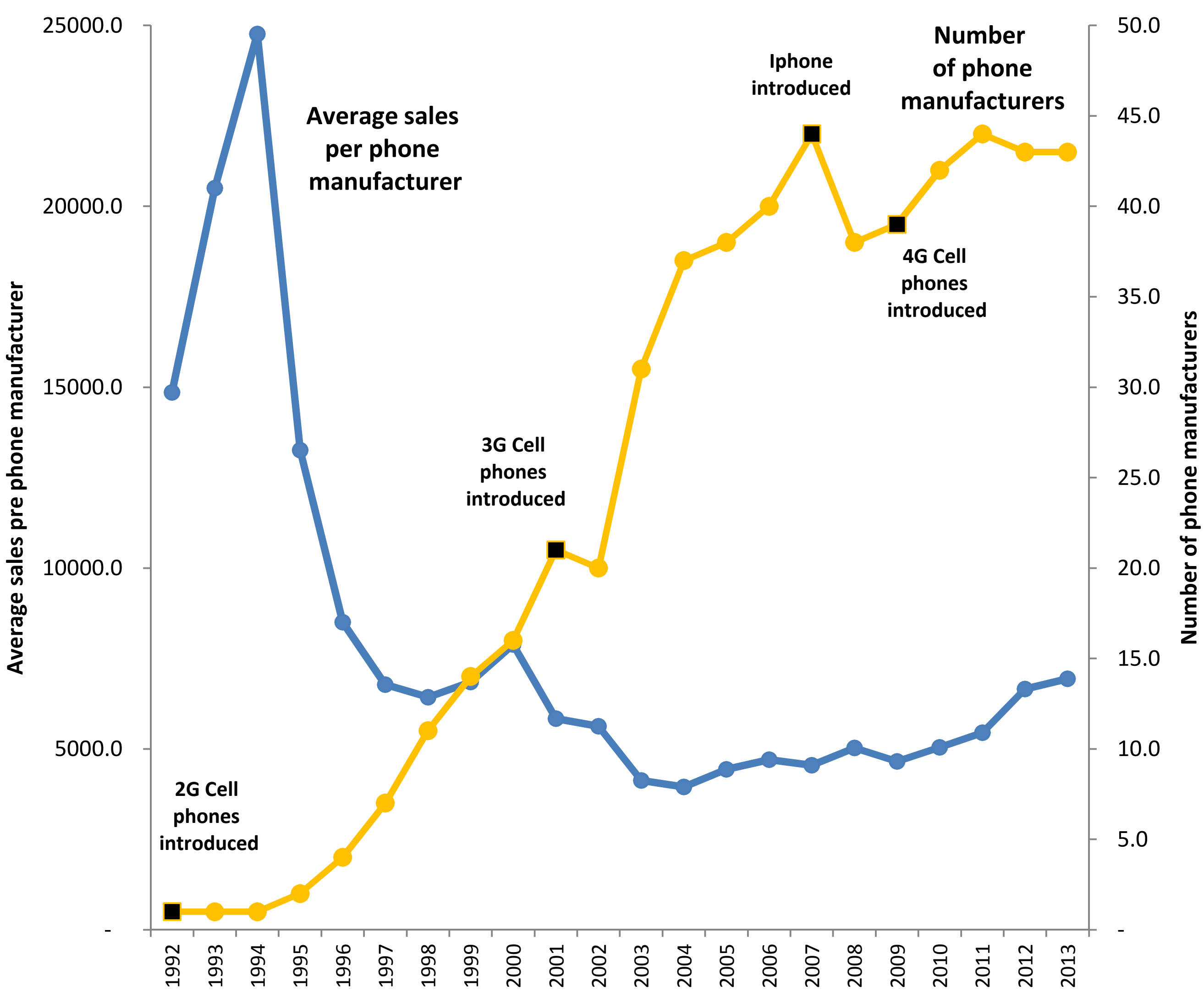
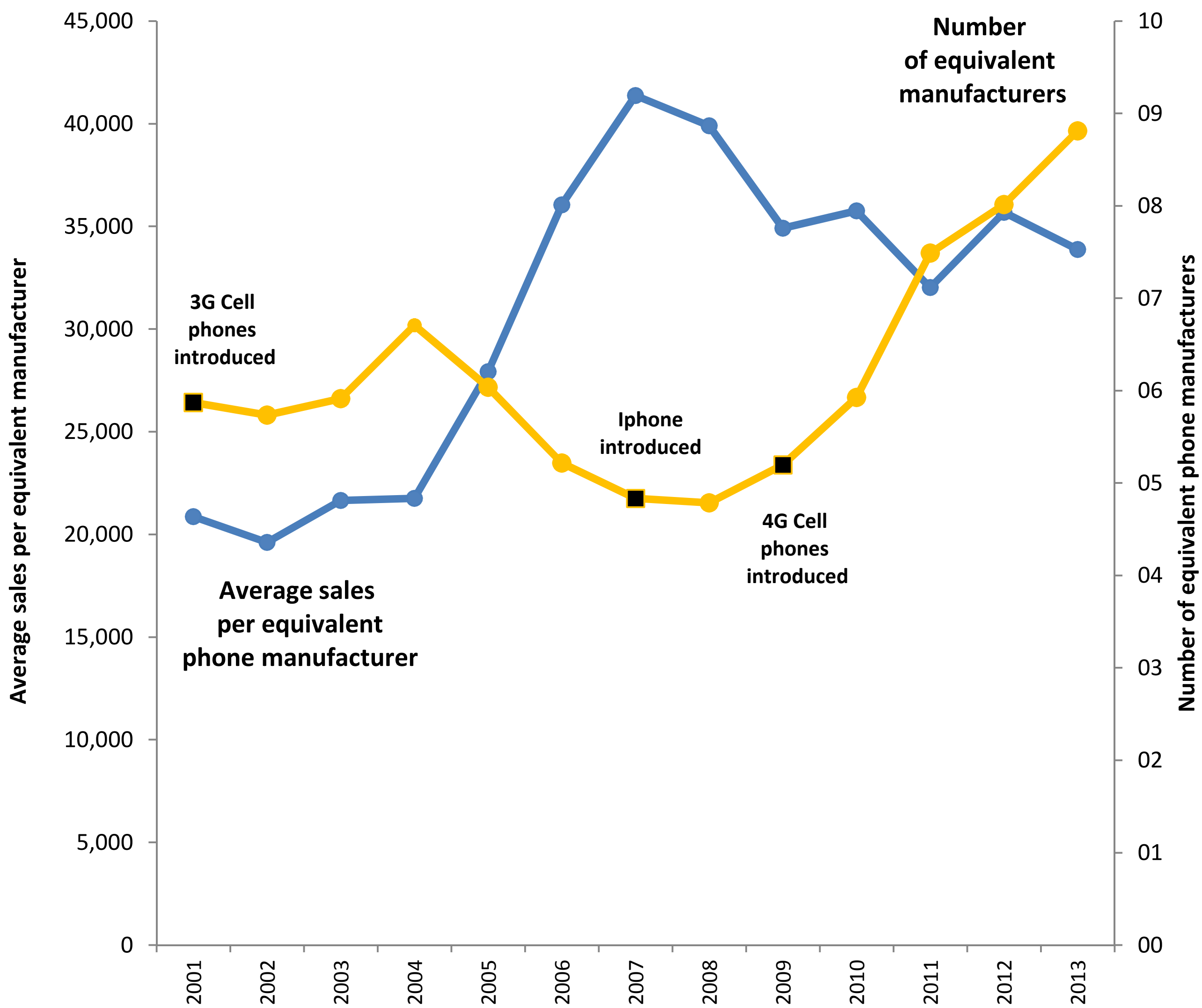


Figure 9
Number of of phone manufacturers and average sales per firm (1992-2013, millions of 2013 $)



This graph shows the evolution of average sales per smartphone manufacturer. Until 2004 the number of firms grew substantially; after 2004, the number stabilized between 40 and 45. Average sales per manufacturer stabilize between 5-7 billion a year ---the number of firms is roughly proportional to market size.

Figure 10
Number of equivalent phone manufacturers and average sales per equivalent firm (2001-2013, millions of 2013 $)



This graph shows the evolution of average sales per smartphone manufacturer. Until 2004 the number of firms grew substantially; after 2004, the number stabilized between 40 and 45. Average sales per manufacturer stabilize between 5-7 billion a year ---the number of firms is roughly proportional to market size.

Figure 11
Average gross margins,
SEP holders (≥ 1 SEP) and rest
(1994-2013)

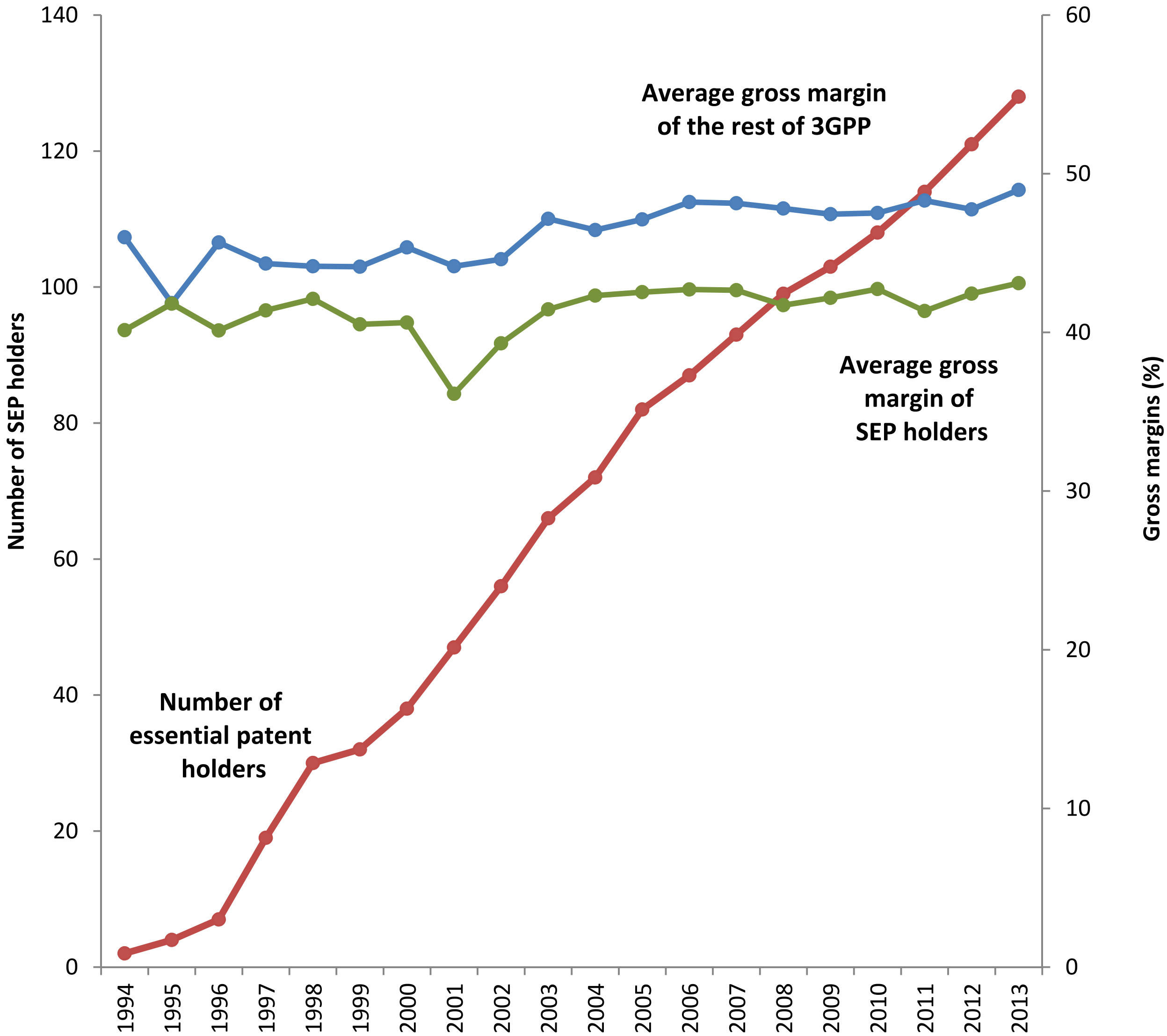


Figure 12
Average gross margins,
SEP holders (≥ 1 SEP) and rest of 3GPP
(device manufacturers)
(1994-2013)

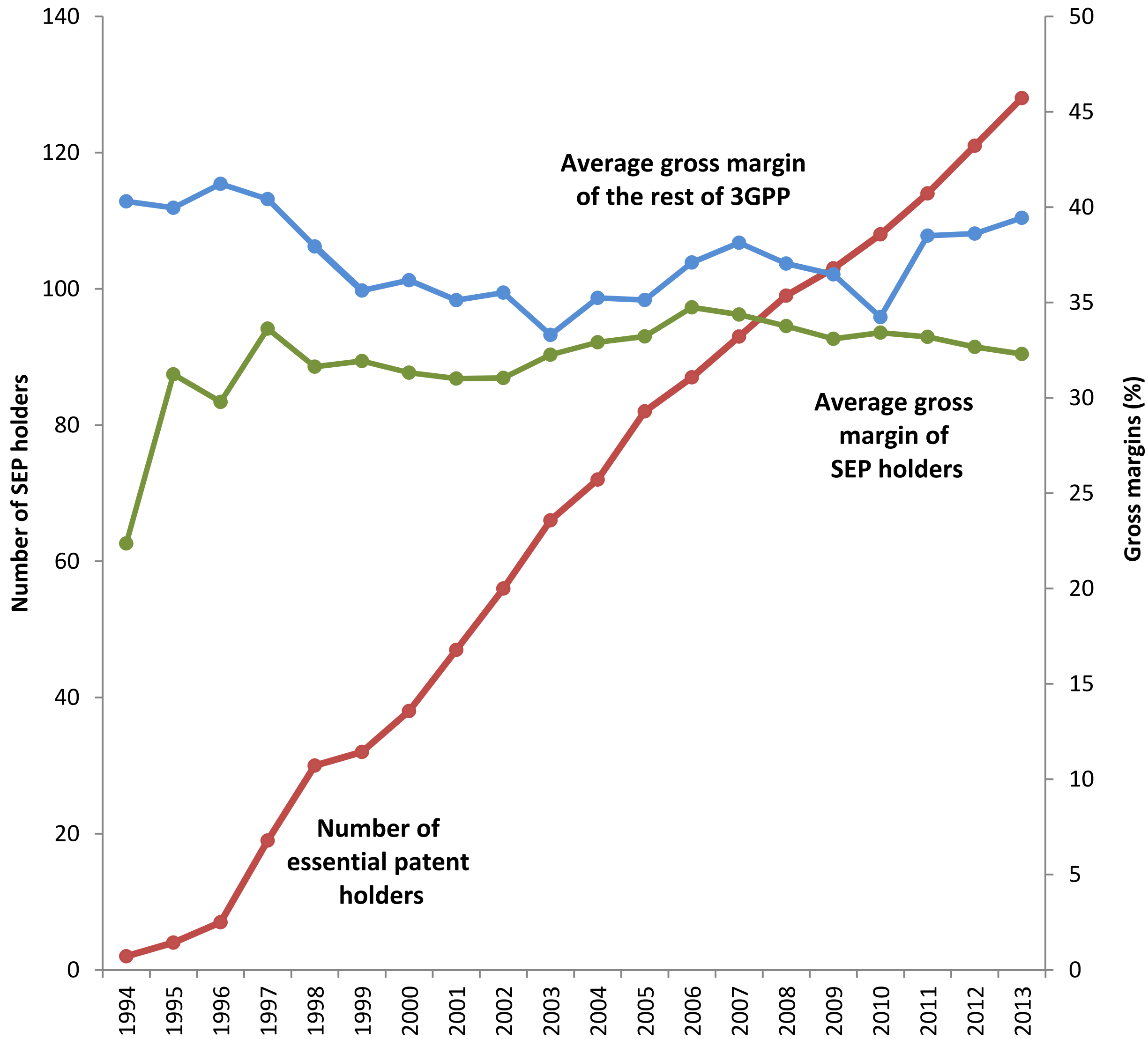


Table 1: The average rate of change across technological generations of the worldwide average selling price

	(1) Coeffcient	(2) Standard error	(3) *t*–value	(4) *p*–value	(5) Predicted price during the first year (in 2013 $)	(6) Average annual rate of change
	Intercepts (α_i)					
1G	9.23	0.15	60.5	0.00	7.959	−21.6%
2G	−1.96	0.18	−11.2	0.00	1.188	−16.6%
2G (GSM)	−1.69	0.18	−9.6	0.00	1.463	−21.6%
2.5G	−2.53	0.19	−13.5	0.00	632	−21.6%
2.5G (GPRS)	−2.64	0.19	−14.0	0.00	547	−24.8%
2.75G (Edge)	−2.73	0.20	−13.8	0.00	519	−21.6%
3G	−2.50	0.19	−13.1	0.00	689	−17.0%
3.5G	−2.93	0.22	−13.6	0.00	480	−11.4%
4G	−3.43	0.28	−12.1	0.00	354	7.6%
	Rate of change (β_i)					
1G	−0.216	0,010	−22.4	0.00		
2G	0.050	0,012	4.3	0.00		
2G (GSM)	0.000	0,012	0.0	0.99		
2.5G	−0.021	0,016	−1.3	0.19		
2.5G (GPRS)	−0.032	0,016	−2.0	0.05		
2.75G (Edge)	−0.028	0,021	−1.3	0.19		
3G	0.046	0,017	2.6	0.01		
3.5G	0.102	0,032	3.2	0.00		
4G	0.292	0,088	3.3	0.00		
n	124					
Groups	9					
R^2	0.972					

The table shows the results of a pooled OLS regression to compute the average yearly rate of fall of the worldwide average selling price of a device of each technological generation. The estimated regression is $\ln p_{i,t_i} = \alpha_1 + \alpha_i \cdot \sum D_i + \beta_1 \cdot t_1 + \beta_i \cdot \sum D_i t_i$, where 1G (*i* = 1) is the base generation. The equation was estimated with pooled OLS. Column 5 shows the predicted price of a device of a given generation during its first year. Column 6 shows the observed average rate of fall of the worldwide average selling price of a device of each generation .

Table 2: Gross margins and number of SEP holders

(Gross margins measured in percentage points)

	1	2	3	4	5	**6**
Number of SEP holders (ten)	−0.005	−0.135	−0.063	0.294**	0.345*	**0.253**
	(0.16)	(0.16)	(0.15)	(0.14)	(0.20)	**(0.21)**
SEP holder dummy (SEP holder = 1)	−7.36***	−5.66***	−5.85***	−5.50***	−5.78***	**−12.14*** **
	(1.29)	(1.44)	(1.46)	(1.35)	(1.35)	**(3.96)**
R&D intensity (one percentage of sales)		−0.003***	−0.003***	−0.004***	−0.004***	**−0.004*** **
		(0.001)	(0.001)	(0.001)	(0.001)	**(0.001)**
Total number of employees (thousands)		−0.078***	−0.094***	−0.076***	−0.076***	**−0.075*** **
		(0.01)	(0.01)	(0.01)	(0.01)	**(0.01)**
Capital stock (billions)		0.142***	0.212***	0.202***	0.204***	**0.195*** **
		(0.04)	(0.04)	(0.03)	(0.03)	**(0.03)**
Component manufacturer			−2.74**	−2.82**	−2.72	**−2.91**
			(1.20)	(1.18)	(2.76)	**(2.76)**
Device manufacturer			−13.24***	−9.01***	−7.20**	**−6.82** **
			(1.40)	(1.42)	(3.36)	**(3.37)**
Other non-manufacturer			2.98	−5.78	3,76	**9.35**
			(4.01)	(3.97)	(17.57)	**(17.86)**
Country dummies				Included	Included	**Included**
nponent manufacturer x number of SEP holders					−0.016	**0.005**
					(0.30)	**(0.30)**
Device manufacturer x number of SEP holders					−0.210	**−0.259**
					(0.36)	**(0.36)**
ther non-manufacturer x number of SEP holders					−0.963	**−1.547**
					(1.71)	**(1.74)**
SEP holder x number of SEP holders						**0.680***
						(0.40)
R2	0.02	0.06	0.12	0.32	0.32	**0.32**
F	16.895	20.593	25.444	26.740	23.959	**23.288**
Observations	1,509					
Number of firms	148					
Period	1994-2013					

The base category for the industry group effects is "infrastructure manufacturer"
(Standard errors in parentheses)
*p<0.10, **p<0.05, ***p<0.01

Table 3: Gross margins and number of SEPs

(Gross margins measured in percentage points)

	1	2	3	4	5	**6**
Number of SEPs (thousand)	0.007	−0.001	0.004	0.022**	0.027*	**0.024**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	**(0.02)**
SEP holder dummy (SEP holder = 1)	−7.51***	−5.88***	−6.07***	−5.75***	−5.71***	**−6.75*** **
	(1.29)	(1.43)	(1.45)	(1.34)	(1.34)	**(2.12)**
R&D intensity (one percentage of sales)		−0.003***	−0.003***	−0.004***	−0.004***	**−0.004*** **
		(0.001)	(0.001)	(0.001)	(0.001)	**(0.001)**
Total number of employees (thousands)		−0.077***	−0.093***	−0.076***	−0.077***	**−0.076*** **
		(0.01)	(0.01)	(0.01)	(0.01)	**(0.01)**
Capital stock (billions)		0.141***	0.210***	0.201***	0.205***	**0.202*** **
		(0.04)	(0.04)	(0.03)	(0.03)	**(0.04)**
Component manufacturer			−2.83**	−2.87**	−2.85	**−2.90**
			(1.20)	(1.19)	(1.74)	**(1.74)**
Device manufacturer			−13.31***	−9.07***	−7.52***	**−7.42*** **
			(1.41)	(1.42)	(2.11)	**(2.11)**
			3.049	−5.764	−3.448	**−2.594**
Other non-manufacturer			(4.01)	(3.97)	(7.58)	**(7.70)**
Country dummies				Included	Included	**Included**
Component manufacturer x number of SEPs					−0.001	**−0.001**
					(0.02)	**(0.02)**
Device manufacturer x number of SEPs					−0.023	**−0.024**
					(0.02)	**(0.02)**
Other non-manufacturer x number of SEPs					−0.030	**−0.041**
					(0.08)	**(0.08)**
SEP holder x number of SEPs						**0.014**
						(0.02)
R2	0.02	0.06	0.12	0.32	0.32	**0.32**
F	17.163	20.566	25.627	26.921	24.146	**23.256**
Observations	1,509					
Number of firms	148					
Period	1994-2013					

The base category for the industry group effects is "infrastructure manufacturer"
Standard errors in parentheses
*p<0.10, **p<0.05, ***p<0.01