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**ROYALTY STACKING AND STANDARD ESSENTIAL PATENTS: THEORY AND  
EVIDENCE FROM THE WORLD MOBILE WIRELESS INDUSTRY**

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

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## Abstract

We build an equilibrium royalty stacking model that links the observable number of SEP holders with prices, quantities, concentration and margins, in principle observable market variables. We show that roughly 10 SEP holders suffice to reduce equilibrium output to about one-tenth of the competitive level; with 100 SEP holders output nearly collapses. As the number of SEP holders increases prices increase; (ii) quantity falls or stagnates; (iii) manufacturers' margins fall; (iv) downstream manufacturing concentrates. Because royalties are endogenous and rise with shocks that increase downstream surplus, neither fast technological change nor falling manufacturing costs can undo the effects of royalty stacking.

We look for royalty stacking in the world mobile wireless industry, where the number of SEP holders for the 2G, 3G, and 4G wireless cellular standards grew from 2 in 1994 to 130 in 2013. We fail to reject the null hypothesis that there is no 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.

JEL classification: L1, O31, O38

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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. On the demand side, standardized technologies enable consumers to interact with devices made by different manufacturers. On the supply side, standards allow R&D, innovation, product development and manufacturing to be decentralized among many firms. Yet an influential literature argues that technological progress in these industries may be under threat. Because standard-compliant products use hundreds, if not thousands of standard-essential patents (SEPs), which are owned by many different SEP holders, one monopoly royalty may stack upon the other and the cumulative royalty may be excessive.<sup>1</sup>

Royalty stacking is an application of the Cournot effect to industries where many firms own patents that read on the same product<sup>2</sup>. As Spulber (2016a,b) has shown, when many monopoly input suppliers post a linear price non cooperatively, they charge more than a single monopolist for the same bundle of inputs. This occurs because, as Spulber (2016b) explains, “[...] in Cournot’s model [...] input suppliers do not take into account the effect of their price increases on the profits of other input suppliers.”<sup>3</sup> Indeed, Shapiro (2001) showed that if  $m$  SEP holders set royalties non cooperatively, the resulting equilibrium margin is  $m$  times the Lerner margin that a bundled monopoly would choose.<sup>4</sup>

Many authors warn that excessive royalties wrought by royalty stacking may discourage investments in manufacturing, stymie the development of new products and, ultimately, may even stop innovation in its tracks. Moreover, antitrust authorities and courts around the world take this threat seriously and think that it warrants vigilance and sometimes action.<sup>5</sup> Yet, as some authors have pointed out, the evidence is still inconclusive, because the royalty stacking hypothesis has not yet been tested.<sup>6</sup>

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<sup>1</sup>A standard-essential patent (SEP) is a patent that reads on an innovation that is potentially essential for the standard to work. This follows the definition of essentiality given, for example, by Assistant 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).

<sup>2</sup>Cournot (1897, ch. 9). On royalty stacking see, for example, Shapiro (2001), Lemley (2007), Lemley and Shapiro (2007 a,b), Golden (2007), Miller (2007), Denicolo et al. (2008), Elhauge (2008), Gerardin, Layne-Farrar and Padilla (2008), Sidak (2008), Schmelensee (2009), Meniere and Parlane (2010), Layne-Farrar and Padilla (2011), Layne-Farrar and Schmidt (2011), Rey and Salant (2012), Gupta (2013), Spulber (2013), Layne-Farrar (2014), Lerner and Tirole (2014), Schmidt (2014), Contreras and Gilbert (2015), Lerner and Tirole (2015), Llobet and Padilla (2016a), Spulber (2016b), and Galetovic and Haber (2017). See also the more general theoretical analysis of Lerner and Tirole (2004, 2015), and Spulber (2016b).

<sup>3</sup>Many writers call it the “Cournot-complement effect,” because in the literature the problem is usually set in a model with complementary inputs. Nevertheless, recently Spulber (2016b) showed that the Cournot effect emerges with innovative substitutes as well and pointed out that the Cournot effect is caused by non-cooperative posted prices, not by complementarity. See also Spulber (2016a).

<sup>4</sup>See also Lerner and Tirole (2004), Lemley and Shapiro (2007), and Spulber (2016b).

<sup>5</sup>See, for example, Federal Trade Commission (2011), Department of Justice and Federal Trade Commission (2007) and Vestager (2016). On court cases, see Judge Robart’s decision on the Motorola vs. Microsoft (2012) case and the recent survey by Barnett (2017).

<sup>6</sup>As Layne-Farrar (2014) notes: “Certainly the theories have been developed, but the empirical support is still

Testing for the presence and effects of royalty stacking is difficult for at least three reasons. One is that royalties charged by SEP holders in bilateral deals are confidential and not observable by researchers. Also, patenting is endogenous and it is difficult to find an exogenous shock to the number of SEP holders. Last, over time “everything else” is not constant and other factors —such as a shifting technological frontier or falling manufacturing costs—may compensate for royalty stacking, masking its effect in market data. One of the consequences of the lack of testing is that it is not still clear whether royalty stacking can derail a market, as some seem to imply; or whether its effects can be compensated by exogenous trends that partially compensate its harmful effects.

This paper contributes to this debate by answering three questions. First, as a matter theory, how much damage can royalty stacking cause and how fast does the damage rise with the number of SEP holders? Second, as a matter of empirics, which are the observable implications of royalty stacking on output, prices, margins and concentration and how can we test the theory? And third, as a matter of policy, can antitrust authorities and courts know whether royalty stacking is happening when neither individual nor the cumulative royalty are observable?

To answer these questions we build a general yet tractable three-stage model where downstream manufacturers decide whether to enter and invest before each SEP holder individually and simultaneously posts her royalty. Then, taking the cumulative royalty as given, manufacturers compete in the product market by setting quantities. On the demand side, we use the family of log-concave, constant rate of 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. On the supply side, we follow Genesove and Mullin (1998) and model the intensity of competition with a conduct parameter, which nests most homogeneous-good oligopoly models.

The first set of results shows that unless the demand curve is nearly vertical, royalty stacking reduces equilibrium output to a very small magnitude very fast and eventually the market collapses. Indeed, roughly 10 SEP holders suffice to reduce equilibrium output to about one-tenth of the competitive level and half the bundled monopoly level; with 100 SEP holders output nearly collapses. Thus the impact of royalty stacking is not marginal but discrete.

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

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

In this demand curve  $Q$  and  $p$  have obvious meanings,  $v < \infty$  is the maximum willingness to pay for a unit of the good,  $\gamma > 0$  is a parameter that determines the curvature of the demand curve,  $S$  is a scale parameter, and output is equal to 100 when price is equal to marginal cost.<sup>7</sup> SEP holders are monopolies and post royalties non cooperatively to maximize profits. If the demand curve is

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lacking. Despite the 15 years proponents of the theories have had to amass evidence, the empirical studies conducted thus far have not shown that holdup or royalty stacking is a common problem in practice.”

<sup>7</sup>That is,  $100 = S(v - c)^\gamma$ . Moreover, in this example (though not in the rest of the paper) we assume that downstream manufacturers are perfectly competitive and there are no licensing costs, so with no patent rights price is equal to the unit cost of manufacturing.

linear ( $\gamma = 1$ ) and there are  $m$  patent holders, equilibrium output is equal to

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

Thus, when only one SEP holder posts a profit maximizing royalty (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 SEP 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 SEP holders reaches 10, output is 9.1—roughly 90 percent lower than with marginal cost pricing. And if the number of SEP 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 SEP holder. As can be seen in Figure 1, output falls at a slower rate when the demand curve is concave and  $\gamma < 1$  and small. But then, the equilibrium price is close to maximum willingness to pay  $v$ , even with only one SEP holder and royalty stacking causes little incremental harm. Therefore, royalty stacking theory has a rather extreme implication: either the industry nearly collapses with a modest number of SEP holders or the demand curve is close to vertical and royalty stacking is nearly irrelevant.

Royalty stacking theory has additional observable implications. One is that the equilibrium price rises fast and a modest number of SEP holders suffice for the cumulative royalty to get close to consumers’ willingness to pay  $v$ ; this is just the flip side of quantities falling fast. Also, and somewhat unexpectedly, equilibrium individual royalties and SEP holders’ margins *fall* with the number of SEP holders because, as the equilibrium downstream price rises, demand becomes more elastic and SEP holders price less aggressively. Indeed, we show that the individual royalty charged by each SEP holder tends to zero fast. Last, as the number of SEP holders increases, manufacturer margins and profits fall, fewer manufacturers enter and equilibrium industry concentration rises. Eventually, when sales are small enough and the industry’s net revenue becomes insufficient to pay for sunk entry costs, entry ceases and the downstream industry collapses.

Because our model links the number of SEP holders, which is observable, with observable market outcomes, researchers can exploit an additional implication of the theory to test the null hypothesis of no royalty stacking in a given industry. The key insight is that both individual royalties and the cumulative royalties are endogenous to the economic surplus that the industry creates. Indeed, we show that when the number of SEP holders is significant, any reduction in manufacturing costs or any technological improvement that increases consumers’ willingness to pay, increases the equilibrium cumulative royalty almost dollar-by-dollar. Consequently, whenever surplus increases, prices rise; quantities do not increase and neither consumers nor manufacturers benefit. Thus, royalty stacking cannot be compensated by countervailing factors that offset the surplus extracted by SEP holders.

We then show that because the cumulative royalty increases almost dollar-by-dollar with any shock that increases downstream surplus, neither prices can fall over time, nor quantities grow in an industry affected by royalty stacking. Hence, in an industry where quantities grow fast and prices fall, the null hypothesis of no royalty stacking cannot be rejected.

We test the observable implications of royalty stacking by examining the evolution of prices, quantities, gross margins, the number of manufacturers and concentration in the world mobile

wireless device industry between 1994 and 2013. As Figure 2 shows, between 1994 and 2013 the number of declared SEPs grew more than 380 times and the number of SEP holders grew from 2 to 130.

Royalty stacking theory predicts that, as the number of SEP holders grows, sales of phones will decline or, if quality increases, stagnate at best. On the contrary, between 1994 and 2013 device sales grew and fast. For example, 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 stacking theory predicts that, as the number of SEP holders grows, the price of a device will increase or, if quality increases, stagnate at best. 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 device generations fell, suggesting that, contrary to the prediction of royalty stacking theory, consumers captured an increasing fraction of the value created by technological progress.<sup>8</sup>

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, contrary to the prediction of royalty stacking theory, show no 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.<sup>9,10</sup>

Our paper is related to the literature on the Cournot effect. Spulber (2016a) synthesizes this literature, shows that the Cournot effect is caused by non-cooperative posted pricing and that bargaining for prices blocks it. He also shows that even with decentralized bargaining between suppliers and manufacturers, two-part tariffs are sufficient to make the problem disappear. We contribute to the literature on the Cournot effect by showing, with a general class of demand functions and downstream oligopoly model, that a finite and many times small number of input suppliers suffice to worsen an industry's performance dramatically.<sup>11</sup> Indeed, the Cournot effect

<sup>8</sup>In the evolution from 2G to 4G technologies, maximum download speeds increased about 12,000 times from 20 kilobits-per-second in 2G to 250 megabits-per-second in 4G.

<sup>9</sup>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).

<sup>10</sup>We measure market shares with the number of devices sold, not the value of sales.

<sup>11</sup>We also show, in Appendix A, 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, in essence, a theory about a market failure, not about input pricing with multiple suppliers in markets that work.

Our paper is also related to the literature on royalty stacking. Like Meniere and Parlane (2010), Rey and Salant (2012), 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 SEP holders.<sup>12</sup> We also extend the model to explore royalty stacking when additional SEP holders add value. We find that then output stagnates and prices increases with each technological improvement.

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.

For example, Teece and Sherry (2003), Gerardin and Rato (2007), Denicolo et. al., (2008), 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.<sup>13</sup> We add to this literature by showing that one cannot reject the null hypothesis of no royalty stacking in the mobile wireless industry.

The rest of the paper is organized as follows. Section 2 develops the theory, links the number of SEP holders with observable outcomes when there is royalty stacking and derives the observable implications of the theory. Section 3 studies the implications of the theory and the restrictions it imposes on observable outcomes. Section 4 applies the theory to the mobile wireless industry. Section 5 concludes with some reflections on why we do not observe royalty stacking.

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is equal to the price elasticity of demand.

<sup>12</sup>Recently, Llobet and Padilla (2016b) have shown that royalty stacking is less severe with ad valorem than with per-unit royalties.

<sup>13</sup>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.

## 2. An equilibrium model of royalty stacking

### 2.1. The model

In this section we study royalty stacking with a three-stage, exogenous sunk cost game with endogenous entry (see Sutton [1991]). Our aim is to study the equilibrium link between the number of SEP holders and observable market outcomes—prices, quantities, concentration and margins. As we will see, this link works through the unobservable cumulative royalty paid by manufacturers.

The time line of the game is in Figure 3. In the first stage (Entry,  $t = 0$ ), manufacturers enter and invest. In the second stage (Royalties,  $t = 1$ ) each SEP holder posts a linear royalty. In the third stage (Competition,  $t = 3$ ) each manufacturer chooses her quantity. We now describe the model.

**Demand** Following Genesove and Mullin (1998) the demand function,  $D$ , is of the form

$$Q = D(p) \equiv S(v - p)^\gamma, \quad (2.1)$$

with  $\gamma > 0$ .  $Q$  and  $p$  have obvious meanings and  $S$  is the size of the market.<sup>14</sup> Parameter  $v < \infty$  is the maximum willingness to pay for a unit. If  $v$  increases, the demand curve and the intercept in the price axis shift upwards. 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 ( $\gamma = 2$ ); and the exponential demand, when  $v, \gamma \rightarrow \infty$  with  $\frac{\gamma}{v}$  constant. It is strictly concave if  $\gamma \in (0, 1)$  and strictly convex if  $\gamma > 1$ . And, with the exception of the limiting exponential demand, willingness to pay is finite and bounded from above by  $v$ . Also, note that

$$\frac{d\frac{D'}{D}}{dp} = -\frac{\gamma}{(v - p)^2} < 0, \quad (2.2)$$

which implies that  $D$  is log concave.<sup>15</sup> Log-concavity ensures quasi concave profit functions, and reaction curves with standard properties. Also the price elasticity is

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

Moreover,

$$\frac{d\eta}{dp} = -\left(\frac{D'}{D} + p \frac{d\frac{D'}{D}}{dp}\right) = \gamma \frac{v}{(v - p)^2} > 0, \quad (2.3)$$

<sup>14</sup>Farbinger and Weyl (2013) call this the constant pass-through class of demand functions due to Bulow and Pfleiderer (1983).

<sup>15</sup>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, as  $\gamma \rightarrow \infty$  the demand curve of the form (2.1) tends to the exponential demand.



and

$$\lim_{p \rightarrow v} \eta(p) = \gamma \lim_{p \rightarrow v} \frac{p}{v - p} = \infty. \quad (2.4)$$

Therefore property (2.2) implies that with bounded willingness to pay, the price elasticity of demand  $\eta$  is increasing in  $p$  and unbounded. This is a fact of some importance below.

**Remark 1.** *Our demand function is similar to the formulations used by Lerner and Tirole (2004 and 2015). In our specification  $v$  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. They model functionalities as a finite set  $I$  and a subset  $S \subseteq I$  of functionalities is a standard. Our formulation can be extended in that direction.*

**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 (2.2). This implies that the elasticity of demand is increasing in price and  $\lim_{p \rightarrow v} \eta(p) = \infty$  (our properties 2.3 and 2.4).*

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

$$Q = D(p) \equiv S(v + p)^\gamma, \quad (2.5)$$

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

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

hence the price elasticity of demand is bounded as  $p$  rises (or  $Q$  falls). Again, this fact is of some importance below. As we will see, it implies that the market disappears if the number of SEP holders is equal or greater than  $-\gamma$ .

**Manufacturers** To enter in  $t = 0$  each manufacturer must invest  $\sigma$  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 is used when manufacturing a component and cannot be invented around. All inventions are complements and components are used in fixed proportions. The unit cost of licensing each essential technology is  $c_\ell$ . Each SEP holder charges a per-unit, linear royalty  $r_j$ . Thus  $\mathcal{R} = \sum r_j$  is the cumulative royalty and  $mc_\ell$  the per-unit cumulative licensing cost. We assume that  $v - c - c_\ell > 0$  to ensure that an equilibrium with production exists when  $m = 1$ , there is no stacking and one SEP holder licenses all patents.<sup>16</sup>

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<sup>16</sup>For the moment we assume that additional inventions do not add any value. Below we extend the model assuming that  $v$  is an increasing function of  $m$ .

**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 Genesove and Mullin’s (1998) variation on Bresnahan (1989). In the short-run, symmetric equilibrium, each firm chooses its output  $q_i$  so that

$$P(Q) + \theta q_i P'(Q) = c + \mathcal{R}, \quad (2.6)$$

where  $\theta$  is the conduct or market power parameter. This formulation nests most static, homogeneous good 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 3. In the first stage (Entry,  $t = 0$ )  $n$  manufacturers invest  $\sigma$ . In the second stage (Royalties,  $t = 1$ ), each SEP holder  $j$  simultaneously and independently posts  $r_j$ , 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 simultaneously sets  $q_i$ , given  $n$  and  $\mathcal{R}$ . Hence our model is an exogenous sunk cost game with endogenous entry, where the conduct parameter  $\theta$  indexes the intensity of competition (see Sutton (1991)).

In what follows we first solve the equilibrium entry game among manufacturers, taking the cumulative royalty as given (section 2.2). Next we examine relation between the cumulative royalty and market outcomes (section 2.3). Then we compute the equilibrium royalty with royalty stacking, and examine their effect on the long-run performance of the industry (section 2.4).

## 2.2. Downstream equilibrium with endogenous entry

**Short-run equilibrium in the product market** We begin with the last stage of the game. 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 (2.6) yields that in a symmetric equilibrium price and quantity are given by

$$p = \frac{\theta v + \gamma n(c + \mathcal{R})}{\theta + \gamma n}, \quad (2.7)$$

and

$$Q = S \left( \frac{\gamma n}{\theta + \gamma n} \right)^\gamma [v - (c + \mathcal{R})]^\gamma. \quad (2.8)$$

Note that equilibrium prices rise as  $n$  falls and concentration increases; this is the standard price-concentration relationship. Note that the pass-through rate of royalties is

$$\frac{\partial p}{\partial \mathcal{R}} = \frac{\gamma n}{\theta + \gamma n} \leq 1. \quad (2.9)$$

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

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

$$\mu \equiv p - (c + \mathcal{R}) = \frac{\theta}{\theta + \gamma n} [v - (c + \mathcal{R})]. \quad (2.10)$$

The Lerner margin is

$$\mathcal{L} \equiv \frac{p - (c + \mathcal{R})}{p} = \frac{\theta v - \theta(c + \mathcal{R})}{\theta v + \gamma n(c + \mathcal{R})}. \quad (2.11)$$

Note that unless the downstream market is perfectly competitive ( $\theta = 0$ ), in the short run margins fall with the cumulative royalty.

**Entry and long-run equilibrium** In the long run, the zero-profit entry condition holds:

$$\mu^* \frac{Q^*}{n^*} \equiv [p^* - (c + \mathcal{R})] \frac{Q^*}{n^*} = \sigma \quad (2.12)$$

(we use a star \* to denote long run equilibrium values). Condition (2.12) says that in the long run structure adjusts so that margin times volume covers the sunk entry cost.

We now solve the entry game. When entering, firms anticipate the short-run game they will play. Hence, substituting the short-run equilibrium quantity (2.8) and margin (2.10) into (2.12) and rearranging yields

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

Now rearrange this expression one more time as

$$n^*(\theta + \gamma n^*) \left( \frac{\theta + \gamma n^*}{\gamma n^*} \right)^\gamma \equiv \phi(n^*; \theta, \gamma) = \frac{S}{\sigma} \theta [v - (c + \mathcal{R})]^{\gamma+1}. \quad (2.13)$$

This expression links equilibrium market structure ( $n^*$ ) with cost, market, and demand parameters ( $c, \sigma; \theta; \gamma, S$ ) and with the cumulative royalty  $\mathcal{R}$ .

The following lemma is useful in what follows.

**Lemma 2.1.**  $\phi' > 0$ .

**Proof:** Totally differentiating  $\phi$  and rearranging yields

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

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

### 2.3. The relation between the cumulative royalty and market outcomes

We now derive the long-run relationship between the cumulative royalty,  $\mathcal{R}$ , which is not observable, and market outcomes that are in principle observable: price, quantity and concentration. In each case we calculate the sign of the effect of an exogenous change of  $\mathcal{R}$ .

To obtain the relation between the cumulative royalty and market structure we totally differentiate both sides of (2.13) and rearrange. This yields

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

**Result 2.2 (The cumulative royalty and concentration).** *In the long run, a higher cumulative royalty  $\mathcal{R}$  reduces the equilibrium number of firms and increases concentration.*

When a higher cumulative royalty

To see how prices vary with an exogenous increase of  $\mathcal{R}$ , replace  $n^*$  into (2.7), totally differentiate with respect to  $\mathcal{R}$  and rearrange. This yields

$$\frac{\partial p^*}{\partial \mathcal{R}} = \frac{\gamma n^*}{\theta + \gamma n^*} - \frac{\theta}{(\theta + \gamma n^*)^2} [v - (c + \mathcal{R})] \frac{\partial n^*}{\partial \mathcal{R}} > 0 \quad (2.14)$$

The impact of higher royalties on the long-run equilibrium price is the sum of two terms. First, the short-run pass through rate  $\frac{\gamma n^*}{\theta + \gamma n^*}$  implies that higher royalties are partially passed through consumers. Second, higher cumulative royalties increase concentration, the industry moves along the price-concentration relationship and prices rise—the second term in (2.14).

Similarly, to see how quantity varies with an exogenous change in  $\mathcal{R}$ , totally differentiate (2.8):

$$\frac{\partial Q^*}{\partial \mathcal{R}} = -\gamma Q^* \left[ \frac{1}{v - (c + \mathcal{R})} - \frac{\theta}{n^*} \frac{\partial n^*}{\partial \mathcal{R}} \right] < 0. \quad (2.15)$$

Hence 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 2.3 (The cumulative royalty, prices and quantities ).** *In the long run, a higher cumulative royalty  $\mathcal{R}$  increases the equilibrium price, and reduces the equilibrium quantity sold.*

In summary, theory predicts that a higher cumulative royalty increases prices, reduces quantities and concentrates the industry.

### 2.4. Royalty stacking and royalties

In this section we study the mechanics of royalty stacking and link the unobservable individual and cumulative royalties with the number of SEP holders, which is in principle observable. We begin with the individual decision of each SEP holder.

**The SEP holder's decision** When setting her royalty each upstream SEP holder takes the number of SEP holders,  $m$ , and the downstream demand curve and behavior as given, and solves

$$\max_r \{(r - c_\ell) \times D(p(\mathcal{R}))\}. \quad (2.16)$$

Because unit costs are constant and the demand function is log concave, there exists a unique, symmetric Cournot equilibrium in prices.<sup>17</sup> 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

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

Define  $\epsilon_m \equiv \frac{\partial p}{\partial \mathcal{R}} \frac{\mathcal{R}_m}{p}$  as the elasticity of downstream equilibrium prices with respect to the cumulative royalty. After some manipulations, we find that

$$\frac{r_m - c_\ell}{r_m} = \frac{m}{\epsilon_m \eta}. \quad (2.17)$$

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 effect: each SEP holder ‘‘sees’’ through the market demand of the final good, summarized by the price elasticity  $\eta$ , and acts as a monopoly ignoring that her royalty reduces the profits made by the other SEP holders.<sup>18</sup> The consequence is that  $m$  monopolists ‘‘stack’’ their royalties and charge  $m$  times the Lerner margin that would be set by a monopoly licensing all patents.<sup>19</sup>

<sup>17</sup>See Vives (1999).

<sup>18</sup>See Shapiro (2001), Lerner and Tirole (2004, p. 695) and Proposition 4(ii) in Lerner and Tirole (2015).

<sup>19</sup>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.

### 2.4.1. Royalty stacking and the cumulative royalty

We now return to the model to explore the relation in equilibrium between the number of SEP holders, royalty stacking and royalties. Straightforward substitutions into equation (2.17) and some algebra yield

$$r_m = \frac{(v - c) + \gamma c_\ell}{m + \gamma}. \quad (2.18)$$

Therefore:

$$\mathcal{R}_m = m r_m = \frac{m}{m + \gamma} [(v - c) + \gamma c_\ell]; \quad (2.19)$$

Hence, as can be readily seen in (2.19):

**Result 2.4 (Royalty stacking and the cumulative royalty).** *In the long run, the cumulative royalty increases with the number of SEP holders.*

### 2.4.2. Royalty stacking and the individual SEP holder

It is apparent from (2.18) that, contrary to the cumulative royalty, 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 2.5 (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 holders becomes large.*

It may be somewhat surprising that individual royalties fall with the number of SEP holders. Yet the result is a straightforward implication of the fact that with log-concave demand and bounded willingness to pay, the elasticity of demand is increasing in price. As the number of SEP holders rises so does the cumulative royalty and the downstream equilibrium price. Consequently, in the game's Nash equilibrium and as the number of SEP holders rises, each individual SEP holder optimizes confronting a more elastic section of the demand curve.

It is also interesting to note how royalty stacking affects SEP holders' individual margins. Some further algebra yields that the equilibrium<sup>20</sup> price-cost margin of each SEP holder is

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

while the corresponding equilibrium Lerner margin is

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

Thus:

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<sup>20</sup>It can be shown that when willingness to pay is unbounded (the class of demand functions with  $\gamma < 0$ ), the individual royalty grows with  $m$ . However, the individual royalty tends to a very large number very fast and the market collapses when  $m$  is close to  $-\gamma$ . Therefore, this class of demand functions almost assumes market collapse wrought by royalty stacking. Because of this, we relegate this class of demand functions to Appendix A.

**Result 2.6.** *If willingness to pay is bounded, then SEP holders' Lerner margins fall as the number of SEP holders rises.*

Note that the cumulative royalty is increasing in  $v - c$ , parameters which summarize consumers' willingness to pay and manufacturing costs and determine the economic surplus created by the downstream market. At the fundamental level, the reason is that the demand for each SEP holder's SEP portfolio is a derived demand. Hence anything that increases economic surplus downstream will raise the equilibrium cumulative royalty.

Now

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

It follows that when  $m$  is large, the cumulative royalty increases nearly dollar by dollar with willingness to pay  $v$ ; it also increases almost dollar by dollar when manufacturing costs  $c$  fall. Hence:

**Result 2.7.** *When the number of SEP holders is large and there is royalty stacking, the downstream equilibrium price will not fall with falling manufacturing costs. Similarly, quality increases will increase the cumulative royalty and equilibrium prices.*

### 3. The observable implications of royalty stacking

#### 3.1. How harmful is royalty stacking?

##### 3.1.1. A benchmark

In this section we ask: how much can royalty stacking hamper the performance of downstream manufacturing? We do so by exploring the relation between on the one hand, the number of SEP holders,  $m$ ; and on the other, quantity and price, which are in principle observable. Our benchmark is a perfectly competitive downstream market with no royalties, which we denote with the superscript  $c$ . In that market

$$p^c = c. \tag{3.1}$$

Substituting into the demand  $D(p) = S(v - p)^\gamma$  yields

$$Q^c = S(v - c)^\gamma. \tag{3.2}$$

We now compare this outcomes with market outcomes with royalty stacking.

##### 3.1.2. Additional SEP holders do not add value

Sometimes it is claimed that SEPs proliferate but create little or no value. If that's the case, what are the observable implications of royalty stacking? Assume that additional SEP holders do not add any value, that is  $v$  does not vary with the number of SEP holders. Some algebra shows that with  $m$  SEP holders

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

is the equilibrium quantity. Hence

$$\frac{Q_m}{Q^c} = \left( \frac{n\gamma}{\theta + n\gamma} \right)^\gamma \left( \frac{\gamma}{m + \gamma} \right)^\gamma \left( 1 - \frac{mc_\ell}{v - c} \right). \quad (3.3)$$

In expression (3.3) the first parenthesis measures the effect of double marginalization on the equilibrium quantity. The second parentheses measures the impact of royalty stacking on quantity.

The worst that double marginalization can get is that downstream firms price as a monopoly. Then  $\theta = n$  and

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

It follows that double marginalization at most adds one margin, similar to one additional SEP holder.

It is apparent from (3.3) that output falls with  $m$  relative to the benchmark  $Q^c$ . Moreover, while the speed with which output falls depends on the curvature of the demand curve, as measured by  $\gamma$ , eventually quantity falls to zero as the number of SEP holders becomes large. How fast?

Figure 4 plots ratio (3.3) in the vertical axis with four different values of  $\gamma$ , assuming that nine manufacturers ( $n = 9$ ) compete à la Cournot ( $\theta = 1$ ) in the downstream market assuming  $Q^c = 100$ .<sup>21</sup> In the horizontal axis we plot the number of SEP holders.

Consider first  $\gamma = 1$  —the linear demand function which was used by Lemley and Shapiro (2007). As the black line in Figure 4 shows, with  $m = 1$  (equivalent to a bundled monopoly)  $\frac{Q_1}{Q^c} = 45$ . 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 relative to  $Q^c$ ; with  $m = 50$  output falls to 1.8 and with  $m = 100$  output falls to 0.9 relative to  $Q^c$ .

Now with  $\gamma = 1.5$  demand is more elastic at each price, and output falls even faster as  $m$  grows. By contrast, with  $\gamma = 0.5$ , demand is less elastic at each price, and output falls a bit slower. But in both cases the effect is significant. Indeed, unless  $\gamma$  is very small and the demand function close to vertical (e.g.  $\gamma = 0.1$ , as shown in Figure 4), the market nearly disappears with  $m \geq 100$ .<sup>22</sup>

Eventually, with  $m$  large enough the market collapses. To see this, recall that the cumulative royalty is

$$\mathcal{R}_m = mr_m = \frac{m}{m + \gamma} [(v - c) + \gamma c_\ell].$$

As  $m$  becomes large,  $\mathcal{R}_m$  tends to  $(v - c) + \gamma c_\ell$ , which is greater than  $v - c$ , the maximum surplus that an economic transaction can create in the downstream market. Thus with  $m$  large enough the Cournot effect is such that SEP holders appropriate all the per-unit economic surplus that the downstream market can create. But because SEP holders use a linear posted price, quantity falls and they destroy all surplus in the process.

<sup>21</sup>For simplicity, we also assume that  $c_\ell = 0$ . As we show in section 4, in 2013 the number of equivalent manufacturers in the wireless device industry was 9. Let  $\mathcal{H}$  be the Herfindahl index. The number of equivalent firms equals  $\frac{1}{\mathcal{H}}$ ; see Adelman (1969).

<sup>22</sup>With  $\gamma$  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 (??)) 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.



While the cumulative royalty that manufacturers pay is not observable, prices are. Some algebra shows that the equilibrium price is

$$p_m = \frac{\theta(m + \gamma) + mn\gamma}{(\theta + n\gamma)(m + \gamma)}v + \frac{n\gamma}{(\theta + n\gamma)} \frac{\gamma}{(m + \gamma)}(c + mc_\ell),$$

a weighted average of  $v$ , the consumer's willingness to pay and  $c + mc_\ell$ , the unit cost of manufacturing and licensing. Moreover,

$$\lim_{m \rightarrow \infty} p_m = v + \frac{n\gamma^2}{\theta + n\gamma} > v.$$

So as  $m$  grows eventually  $p$  gets close to  $v$  and then the market collapses because no surplus is left.

It follows that one observable implication of the model is that even with a modest number of SEP holders, the effect of royalty stacking on output is severe and eventually, output collapses. One way or another, royalty stacking is not about marginal effects; on the contrary, it predicts market failure wrought by posted, linear royalties. Hence:

**Result 3.1 (Royalty stacking with SEP holders who add no value).** *If additional SEP holders add no value, output falls fast with the number of SEP holders. With  $m$  large enough the market collapses.*

### 3.1.3. Additional SEP holders add value

So far we have assumed fixed  $v$  and  $c$ . One may argue, however, that many products improve over time with the addition of new functionalities contributed by a growing number of SEP holders.<sup>23</sup>

To study the interaction of quality improvements and royalty stacking, we follow Lerner and Tirole (2004) and assume that  $v \equiv m\mathcal{V}$ . That is, SEP holders contribute valuable features which linearly increase users' willingness to pay  $v$ . We also assume that  $c \equiv m\zeta$ —better products are more expensive to manufacture. Because  $\mathcal{V}$  and  $m$  are parameters, we can just substitute  $m\zeta$  into (3.1), to obtain our new benchmark:

$$p^c = c = m\zeta.$$

Moreover, substituting  $m\zeta$  and  $m\mathcal{V}$  into the demand  $D(p) = S \cdot (v - p)^\gamma$  yields

$$Q^c = Sm^\gamma(\mathcal{V} - \zeta)^\gamma.$$

Note that now price increases over time as manufacturing becomes more complex. More important, quantity increases over time as products get better, because consumers' willingness to pay increases accordingly.

If there is royalty stacking, however, some algebra shows that in equilibrium

$$Q_m = S \left( \frac{n\gamma}{\theta + n\gamma} \right)^\gamma \left( \frac{\gamma}{1 + \frac{\gamma}{m}} \right)^\gamma (\mathcal{V} - \zeta - c_\ell)^\gamma. \quad (3.4)$$

<sup>23</sup>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  $v$ .

As can be seen from (3.4), the number of SEP holders grows, quantity slowly grows as  $\frac{\gamma}{m}$  falls, but eventually stagnates, as  $\frac{\gamma}{m}$  tends to 0. So technological progress wrought by new technologies does not increase sales if SEP holders post royalties and there is royalty stacking.

To discuss the economics, note that now the individual royalty is

$$\frac{1}{1 + \frac{\gamma}{m}} \left[ (\mathcal{V} - \zeta) + \frac{\gamma c_\ell}{m} \right].$$

So when the number of patent holders is large, the individual royalty tends to  $\mathcal{V} - \zeta$ : each SEP holder appropriates her incremental contribution to value. Consequently, the cumulative royalty increases linearly with the number of SEP holders, that is

$$\mathcal{R}_m = mr_m \approx m(\mathcal{V} - \zeta).$$

The economics at work is, as Result 2.7 shows, with royalty stacking and enough SEP holders, the cumulative royalty increases almost dollar by dollar with users' willingness to pay. This will increase the equilibrium price. Indeed, some algebra shows that

$$p_m = \frac{\theta(m + \gamma) + mn\gamma}{(\theta + n\gamma)(m + \gamma)} m\mathcal{V} + \frac{n\gamma}{(\theta + n\gamma)(m + \gamma)} \frac{\gamma}{m} (\zeta + c_\ell) \approx m\mathcal{V};$$

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

**Result 3.2 (Royalty stacking with SEP holders who add value).** *With royalty stacking and a large number of SEP holders the cumulative royalty grows without bound, prices increase dollar by dollar with willingness to pay, and the market stagnates.*

### 3.2. Can exogenous trends in technology and costs mask royalty stacking?

Over time “everything else” is not constant and exogenous factors —such as a shifting technological frontier, falling manufacturing costs or falling manufacturing margins forced by more intense competition—might compensate for royalty stacking, masking its effect in market data. Nevertheless, recall that as Result 2.7 shows,

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

It follows that when  $m$  is large, the cumulative royalty increases nearly dollar by dollar with willingness to pay  $v$ ; it also increases almost dollar by dollar when manufacturing costs  $c$  fall.

Therefore, an important implication of Result 2.7 is that the effect of higher royalties wrought by royalty stacking in the downstream market cannot be masked by exogenous market trends that raise willingness to pay (say, because expanding technological opportunity creates better products) or reduce manufacturing costs; or by any other trend that increases economic surplus. Of course, like when the increased willingness to pay is caused by new technologies contributed by SEP holders, with royalty stacking exogenous technological improvements appear in rising prices, as SEP holders capture most of the incremental value. For the same reason, quantities will not grow; at best they will stagnate.

### 3.3. Testing the null hypothesis of no royalty stacking

As we have seen, our theory links the number of SEP holders, which is observable, with market outcomes that are in principle observable, when SEP holders post linear royalties non cooperatively and a Cournot effect is at work. More important, royalty stacking theory delivers at least four predictions.

One is that with a significant and growing number of SEP holders quantities at least stagnate (if there is fast technological progress) and may fall over time (if additional SEP holders add no value). Also, prices increase over time; if there is technological progress that increases consumers' willingness to pay, prices increase even faster. At the same time, concentration increases over time or at least does not fall. Last, downstream Lerner margins tend to zero as the number of SEP holders grows; and SEP holders' Lerner margin either fall (if there is fast technological progress) or show no trend (if additional SEP holders add no value).<sup>24</sup>

At the same time, royalty stacking excludes some market outcomes. If the number of SEP holders grows over time, quantities cannot increase over time; prices cannot fall; concentration cannot fall; downstream Lerner margins can neither increase nor show no trend. Hence, theory restricts observable market outcomes and these restrictions can be used to test the null hypothesis of no royalty stacking. Indeed, if in a market prices fall, quantities increase, concentration falls, and downstream Lerner margins increase or show no trend, the null hypothesis of no royalty stacking cannot be rejected. In the next section we apply this test to the world mobile wireless industry.

## 4. An application: is there royalty stacking in the mobile wireless industry?

In this section 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. To provide some context, we begin with a brief description of standard setting in the mobile wireless industry.

### 4.1. 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. SSOs and the standards they develop 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 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

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<sup>24</sup>See Appendix B.

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).<sup>25</sup> 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 *kilobits-per-second* in 2G to 250 *megabits-per-second* in 4G. Standards also allow specialization (see Figure 5). 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.<sup>26</sup> 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).<sup>27</sup> 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 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

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<sup>25</sup>Baron and Gupta (2015) describe and explain the process of 3GPP standard setting.

<sup>26</sup>Some standards bodies produce open standards, i.e., participants forfeit their IPR 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.

<sup>27</sup>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).

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.

## 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. Figure 6 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 SEP holders. Now as can be seen in Figure 6, between 1994 and 2013 the number of SEP holders grew from 2 to 130. Royalty stacking 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 6, 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 7<sup>28</sup>. 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 SEP holders go after consumer surplus. And the effect should worsen over time as the number of SEP holders is increasing over time.

Figure 7 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

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<sup>28</sup>This is a variant of a hedonic price, 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).

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.<sup>29</sup>

### 4.3. Market structure

Royalty stacking theory also predicts that the industry will concentrate as the number of SEP holders rises. Figure 8 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.<sup>30</sup>

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 9 plots the number of equivalent device manufacturers<sup>31</sup>. 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 SEP holders add no value, SEP holders’ and manufacturer’s Lerner margins should fall with royalty stacking. By contrast, if SEP 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 com-

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<sup>29</sup>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 downstream market power is not quantitatively very relevant.—it can be at most equivalent to one additional patent holder.

<sup>30</sup>We describe the data in Appendix C.

<sup>31</sup>The Herfindahl index is usually measured with sales, but we do not have firm-level sales.

puted gross margins year by year.<sup>32,33</sup> 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.

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:

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

The first coefficient,  $\alpha_1$ , measures the effect on margins of the cumulative number of SEP holders. The second coefficient,  $\alpha_2$ , measures whether SEP holders have systematically different margins.

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<sup>32</sup>The gross margin is 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).

<sup>33</sup>We calculated gross margins with data from Thomson One. Each year we divided each firm’s gross profit by total revenues as reported on the firm’s financial statement.

The third coefficient,  $\alpha_3$ , measures whether the number of SEP holders has a systematic differential effect on SEP-holder’s margins.

We also control for other determinants of gross margins. First, firm-specific characteristics: R&D intensity ( $\beta_1$ ), the number of employees ( $\beta_2$ ) and the size of the capital stock ( $\beta_3$ ). 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 ( $\gamma_1$ ), a device manufacturer ( $\gamma_2$ ) and other non-manufacturer ( $\gamma_3$ ). Third, a fixed effect controlling for the country where the firm’s headquarter is located ( $\delta_1$ ). Last, we add interaction terms between the firm’s place in the value chain and the number of SEP holders ( $\xi_i$ ).

If additional SEP 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,  $\alpha_3$ , may be positive or negative, but in any case  $\alpha_1 + \alpha_3 < 0$ . If, on the other hand, SEP holders add value, then the model still predicts that manufacturers’ margins should fall, so  $\alpha_1 < 0$ . But now the interaction term,  $\alpha_3$ , 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 ( $\alpha_1$ ) and a dummy variable for SEP holders ( $\alpha_2$ ). 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,  $R^2$ s grow as we 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,  $R^2$ s do not change with interaction terms, which depend on the number of SEP holders (regressions 6 and 7). Therefore, firm characteristics, the place in the value chain, and especially, the country where the firm is located, explain around one-third of the variation in margins. By contrast, there is no relation between margins and the number of SEP holders, which is inconsistent with royalty stacking.

Column 6 in Table 2, which shows the regression with all controls added, confirms this conclusion. 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 rises 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



royalty stacking hypothesis predicts change in the opposite direction when patents are worthless.

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 SEP 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 the number 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.

We 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.

Margins affect patenting and the number of SEP holders. With royalty stacking there should be less innovation and patenting, because the market shrinks. However, as the number of firms falls, margins recover somewhat. So in a regression like (4.1), the absolute size of the coefficient of the number of SEP holders,  $\alpha_1$ , would be biased downwards in absolute value. Nevertheless with severe royalty stacking the biased coefficient must still be negative because manufacturer exit cannot fully reverse the fall of margins—otherwise royalty would prompt entry, not exit of manufacturers.

## 5. Conclusion

Many think that royalty stacking is harmful and several authors have proposed amendments to the standard setting process aimed at lowering royalties charged by SEP holders.<sup>34</sup> 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.” We have shown that the fear of royalty stacking is, to some extent, warranted, for about 10 SEP holders may be enough to dramatically reduce equilibrium output. Indeed, with royalty stacking an industry cannot grow and prices cannot fall, even if exogenous trends improve products and reduce manufacturing costs.

At the same time, we have shown that in the mobile wireless industry prices have fallen, quantities have grown and the industry has become less concentrated over time. 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-

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<sup>34</sup>See, for example, Lerner and Tirole (2014, 2015), Swanson and Baumol (2005), Skitol (2005) Farrell et al. (2007), Lemley and Shapiro (2013), and Llanes and Poblete (2014).

reliant products. Indeed, they fell fast relative to the prices of almost any other good, suggesting fast and sustained innovative activity. These outcomes are not consistent with royalty stacking. Why is the Cournot effect missing in these industries?

Recent work offers complementary explanations. First, as Spulber (2016b) notes, in practice licenses are not posted prices but they are usually fixed in bilateral bargaining to split the surplus created. Spulber shows that bilateral bargaining blocks the Cournot effect, because when patent holders offer licenses to manufacturers, they take into account the effect of their offers on final output. Perhaps more important, output is at least as large as with a bundled monopoly and may be even larger, if inventions are innovative substitutes. Indeed, Kretschmer and Reitzig (2016) show that in industries with complementary inputs and network markets, R&D endogenously adapts to develop substitute solutions for the same component.

Second, as Galetovic, Haber and Zaretzki (2017) note, a crucial aspect of Cournot's example is that it deals with physical inputs: if the manufacturer does not agree to the posted price, the input monopolist can refuse to ship and shut down production. By contrast, it is not a fact of nature that the production of a SEP-intensive good requires the payment of patent licenses. Rather, manufacturers can produce and then force SEP holders to use the legal system in order to be paid. Therefore, courts set the royalty in the event of disagreement.

In litigation the manufacturer has an incentive to claim that the patents are invalid, and thus that he should pay no royalties. If he loses, then he pays what the court determines is a reasonable royalty, which is not higher than the asking price. But, if he wins on this claim, then the patent holder not only sees its prospective royalties reduced or eliminated for this manufacturer; his earnings from all other prospective licensees may also be reduced or eliminated. Hence the manufacturer knows that if the licensor asks for an "excessive" royalty he can litigate to pay a lower royalty or avoid paying altogether. As this is common knowledge, each party makes efforts to ascertain the likely scenarios in litigation and backward-inducts to create bids and asks.

Indeed, in an intriguing recent paper, Llobet and Padilla (2016b) show that the threat of litigation not only disciplines individual SEP holders but creates a strategic interaction that blocks royalty stacking. If only a subset of patent holders, those with a weak patent portfolio, face a threat of litigation, then patent holders with strong portfolios may have a strategic incentive to charge lower royalties to force weak patent holders to charge even lower royalties to avoid litigation.<sup>35</sup> This "inverse Cournot effect" ensures a lower equilibrium cumulative royalty, higher equilibrium downstream output and higher royalty income for patent holders with a strong portfolio.

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<sup>35</sup>Interestingly, in Llobet and Padilla's model the likelihood of litigation depends on the difference between the royalty asked by an individual SEP holder with a weak patent portfolio and the cumulative royalty charged by all SEP holders. Furthermore, if the cumulative royalty is high, the expected gains from invalidating the portfolio of a SE holder are less likely to compensate for the costs incurred by the licensee, because in a high-cumulative royalty industry output is small. Therefore, by lowering her royalty a SEP holder with a strong portfolio disciplines SEP holders with weak portfolios.

# Appendix

## A. Royalty stacking with unbounded willingness to pay

### A.1. Demand

Consider demand function (2.5) in the text

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

with  $\gamma < 0$  and  $v \in \mathbb{R}$ . When  $v < 0$  the quantity demanded approaches infinity as  $p \rightarrow -v$  and approaches 0 as  $p \rightarrow \infty$ . 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  $\lim_{p \rightarrow \infty} \eta(p) = -\gamma$ . On the other hand, if  $v < 0$ ,  $p$  is bounded below by  $-v$ ,  $\lim_{p \rightarrow -v} \eta(p) = \infty$ ,  $\eta'(p) < 0$  and  $\lim_{p \rightarrow \infty} \eta(p) = -\gamma$ . Last, when  $v = 0$  this yields the constant-elasticity demand with  $\eta = -\gamma$ .

### A.2. Downstream equilibrium

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

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

Standard manipulations of the first order condition (2.6) yields that in a symmetric equilibrium

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

and

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

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 (2.9).<sup>36</sup> 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.3. Royalty stacking

Assume that demand is of the form (2.5) 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

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

and

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

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<sup>36</sup>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.

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

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

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.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  $\sigma$  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 (2.5) 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

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

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  $\gamma$  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.5. Royalty stacking and increasing SEP margins

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

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

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

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.

## B. Lerner margins and royalty stacking

In this appendix we show that manufacturers' Lerner margins tend to zero as the number of SEP holders increases. Recall that from equation (2.11) we know that the lerner margin of a manufacturer is

$$\mathcal{L}_m \equiv \frac{p_m - (c + \mathcal{R}_m)}{p_m} = \frac{\theta(v - (c + \mathcal{R}_m))}{\theta v + \gamma n_m^*(c + \mathcal{R}_m)}.$$

Hence

$$\lim_{m \rightarrow \infty} \mathcal{L}_m = \frac{\theta(v - (c + \lim_{m \rightarrow \infty} \mathcal{R}_m))}{\theta v + \gamma(\lim_{m \rightarrow \infty} n_m^*)(c + \lim_{m \rightarrow \infty} \mathcal{R}_m)}.$$

If SEP holders do not add any value, then

$$\lim_{m \rightarrow \infty} \mathcal{R}_m = \lim_{m \rightarrow \infty} \frac{m}{m + \gamma} [v - c + \gamma c_\ell] = [v - c + \gamma c_\ell].$$

Hence

$$\lim_{m \rightarrow \infty} \mathcal{L}_m = -\frac{\gamma c_\ell}{\theta v + \gamma(\lim_{m \rightarrow \infty} n_m^*)(v + \gamma c_\ell)} < 0.$$

If SEP holders add value, then  $v = m\mathcal{V}$  and  $m\zeta$ . Hence,

$$\mathcal{R}_m = \frac{m^2}{m + \gamma} \left[ \mathcal{V} - \zeta + \frac{\gamma c_\ell}{m} \right]$$

and

$$\mathcal{L}_m \equiv \frac{p_m - (c + \mathcal{R}_m)}{p_m} = \frac{\theta(m\mathcal{V} - (m\zeta + \mathcal{R}_m))}{\theta m\mathcal{V} + \gamma n_m^*(m\zeta + \mathcal{R}_m)}.$$

It follows that when  $m$  is large,

$$\mathcal{R}_m \approx m(\mathcal{V} - \zeta)$$

and

$$\mathcal{L}_m \approx \frac{\theta(m\mathcal{V} - (m\zeta + m(\mathcal{V} - \zeta)))}{\theta v + \gamma n_m^*(m\zeta + m(\mathcal{V} - \zeta))} \approx 0.$$

## C. Data description

### C.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 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.

### C.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.

### C.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](http://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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**Table 1: The average rate of change across technological generations of the worldwide average selling price**

	(1) Coefficient	(2) Standard error	(3) <i>t</i> -value	(4) <i>p</i> -value	(5) Predicted price during the first year (in 2013 \$)	(6) Average annual rate of change
Intercepts ( $\alpha_i$ )						
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 ( $\beta_i$ )						
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		
<i>n</i>	124					
Groups	9					
R <sup>2</sup>	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 (0.16)	-0.135 (0.16)	-0.063 (0.15)	0.294** (0.14)	0.345* (0.20)	<b>0.253</b> <b>(0.21)</b>
SEP holder dummy (SEP holder = 1)	-7.36*** (1.29)	-5.66*** (1.44)	-5.85*** (1.46)	-5.50*** (1.35)	-5.78*** (1.35)	<b>-12.14***</b> <b>(3.96)</b>
R&D intensity (one percentage of sales)		-0.003*** (0.001)	-0.003*** (0.001)	-0.004*** (0.001)	-0.004*** (0.001)	<b>-0.004***</b> <b>(0.001)</b>
Total number of employees (thousands)		-0.078*** (0.01)	-0.094*** (0.01)	-0.076*** (0.01)	-0.076*** (0.01)	<b>-0.075***</b> <b>(0.01)</b>
Capital stock (billions)		0.142*** (0.04)	0.212*** (0.04)	0.202*** (0.03)	0.204*** (0.03)	<b>0.195***</b> <b>(0.03)</b>
Component manufacturer			-2.74** (1.20)	-2.82** (1.18)	-2.72 (2.76)	<b>-2.91</b> <b>(2.76)</b>
Device manufacturer			-13.24*** (1.40)	-9.01*** (1.42)	-7.20** (3.36)	<b>-6.82**</b> <b>(3.37)</b>
Other non-manufacturer			2.98 (4.01)	-5.78 (3.97)	3.76 (17.57)	<b>9.35</b> <b>(17.86)</b>
Country dummies				Included	Included	<b>Included</b>
Component manufacturer x number of SEP holders					-0.016 (0.30)	<b>0.005</b> <b>(0.30)</b>
Device manufacturer x number of SEP holders					-0.210 (0.36)	<b>-0.259</b> <b>(0.36)</b>
Other non-manufacturer x number of SEP holders					-0.963 (1.71)	<b>-1.547</b> <b>(1.74)</b>
SEP holder x number of SEP holders						<b>0.680*</b> <b>(0.40)</b>
R2	0.02	0.06	0.12	0.32	0.32	<b>0.32</b>
F	16.895	20.593	25.444	26.740	23.959	<b>23.288</b>
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)

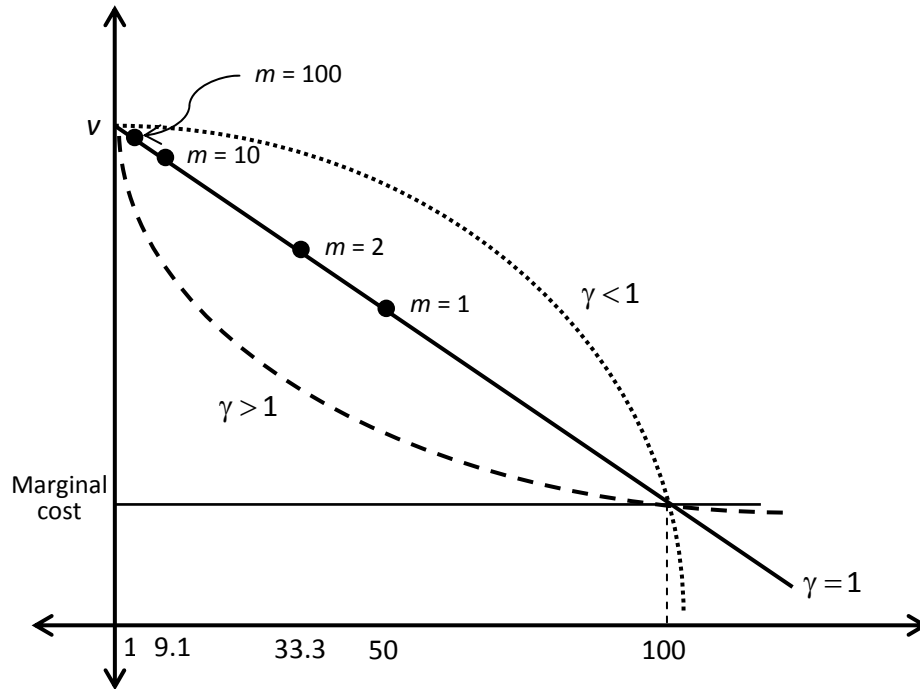
	1	2	3	4	5	6
Number of SEPs (thousand)	0.007 (0.01)	-0.001 (0.01)	0.004 (0.01)	0.022** (0.01)	0.027* (0.01)	<b>0.024</b> <b>(0.02)</b>
SEP holder dummy (SEP holder = 1)	-7.51*** (1.29)	-5.88*** (1.43)	-6.07*** (1.45)	-5.75*** (1.34)	-5.71*** (1.34)	<b>-6.75***</b> <b>(2.12)</b>
R&D intensity (one percentage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

The base category for the industry group effects is "infrastructure manufacturer"

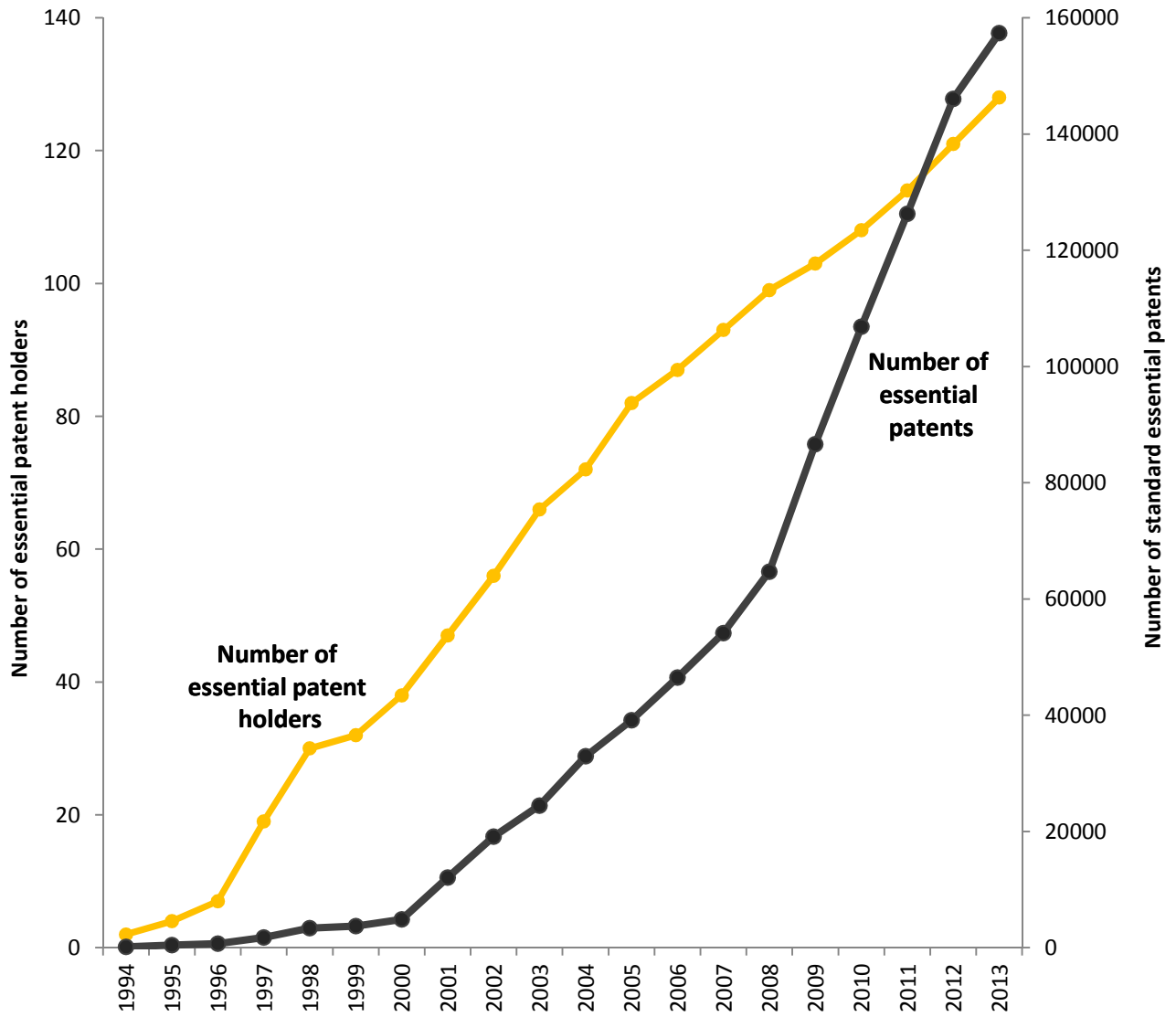
Standard errors in parentheses

\*p&lt;0.10, \*\*p&lt;0.05, \*\*\*p&lt;0.01

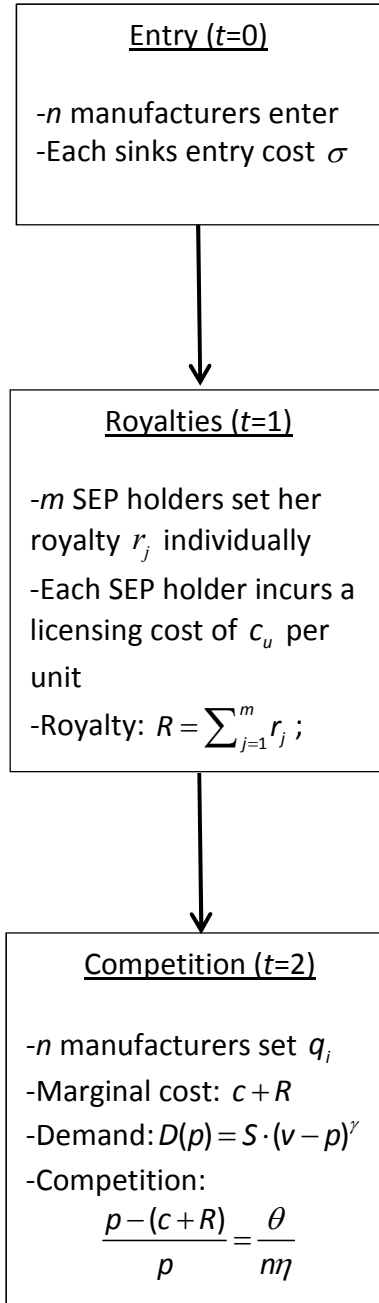
**Figure 1**  
**Royalty stacking with constant pass-through,**  
**log-concave demand**



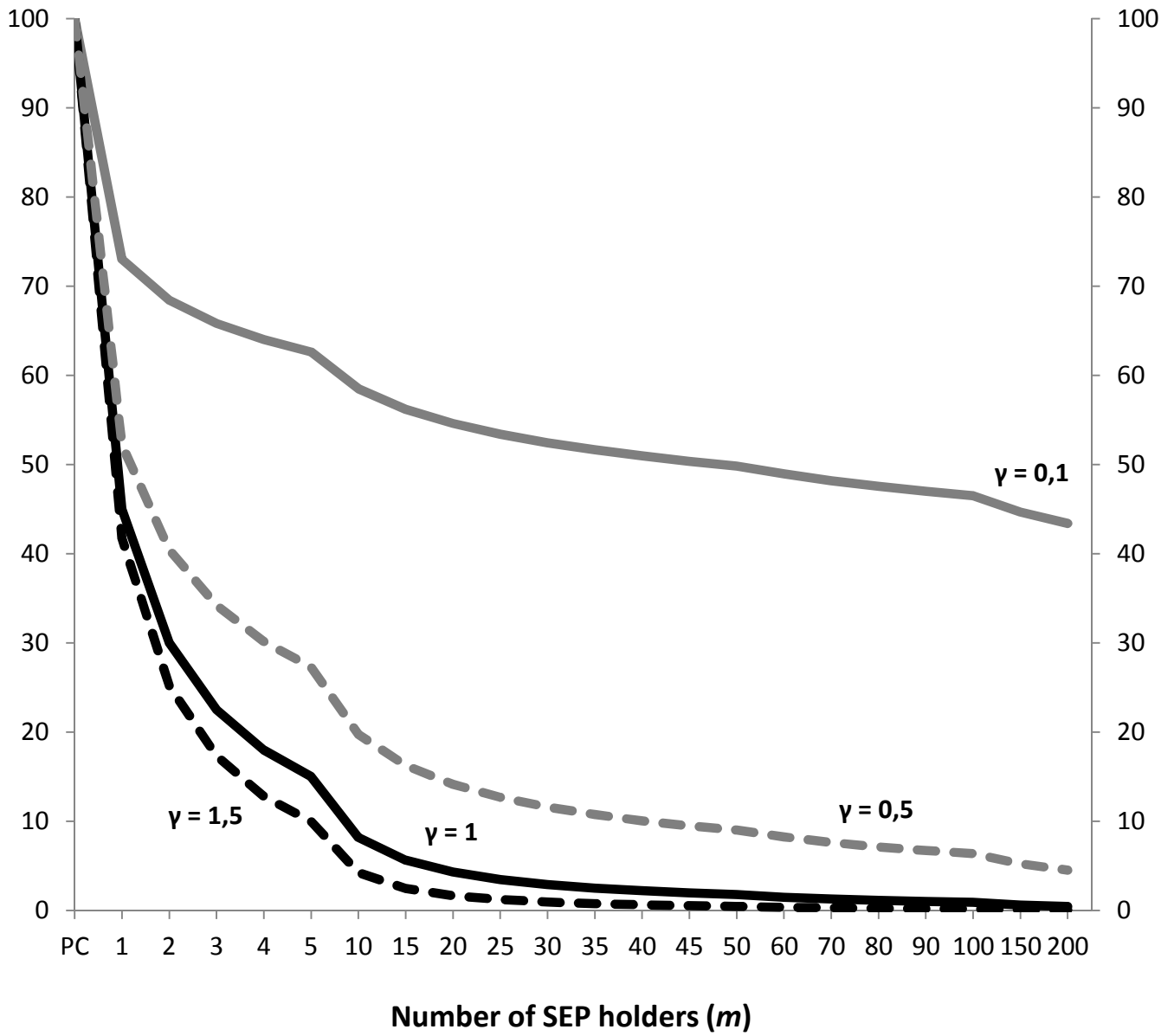
**Figure 2**  
**Number of SEPs and SEP holders**  
**(1994-2013)**



**Figure 3: the royalty stacking game**

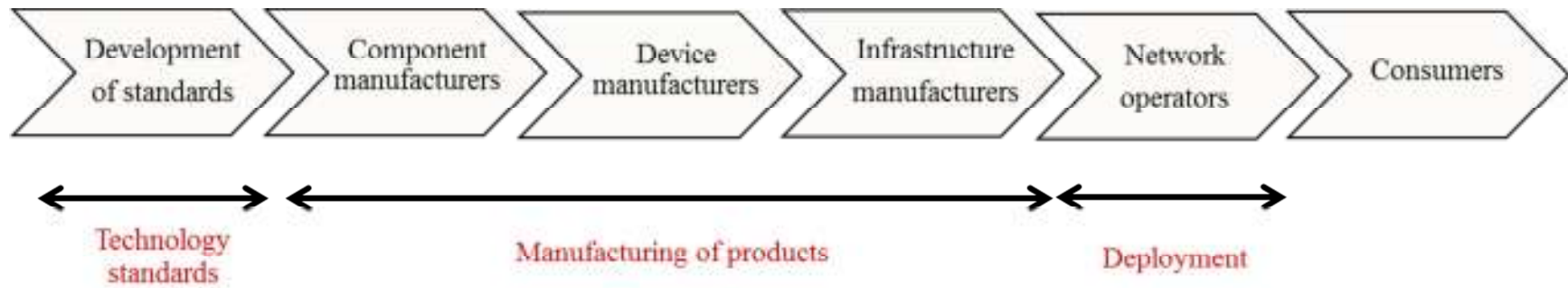


**Figure 4**  
**Equilibrium quantity and the number of SEP holders**  
 $100 = Q(c+mc_e)$

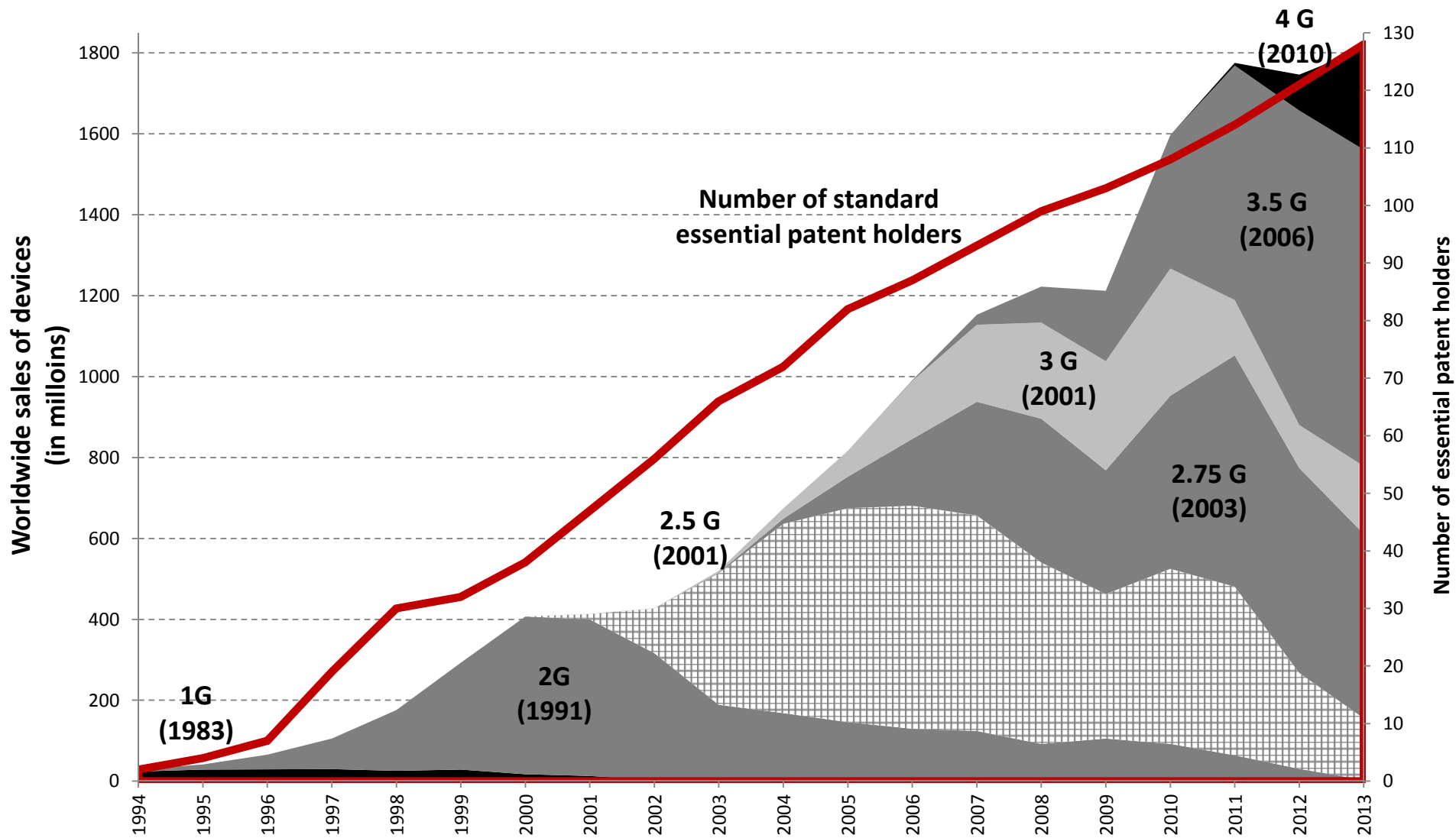




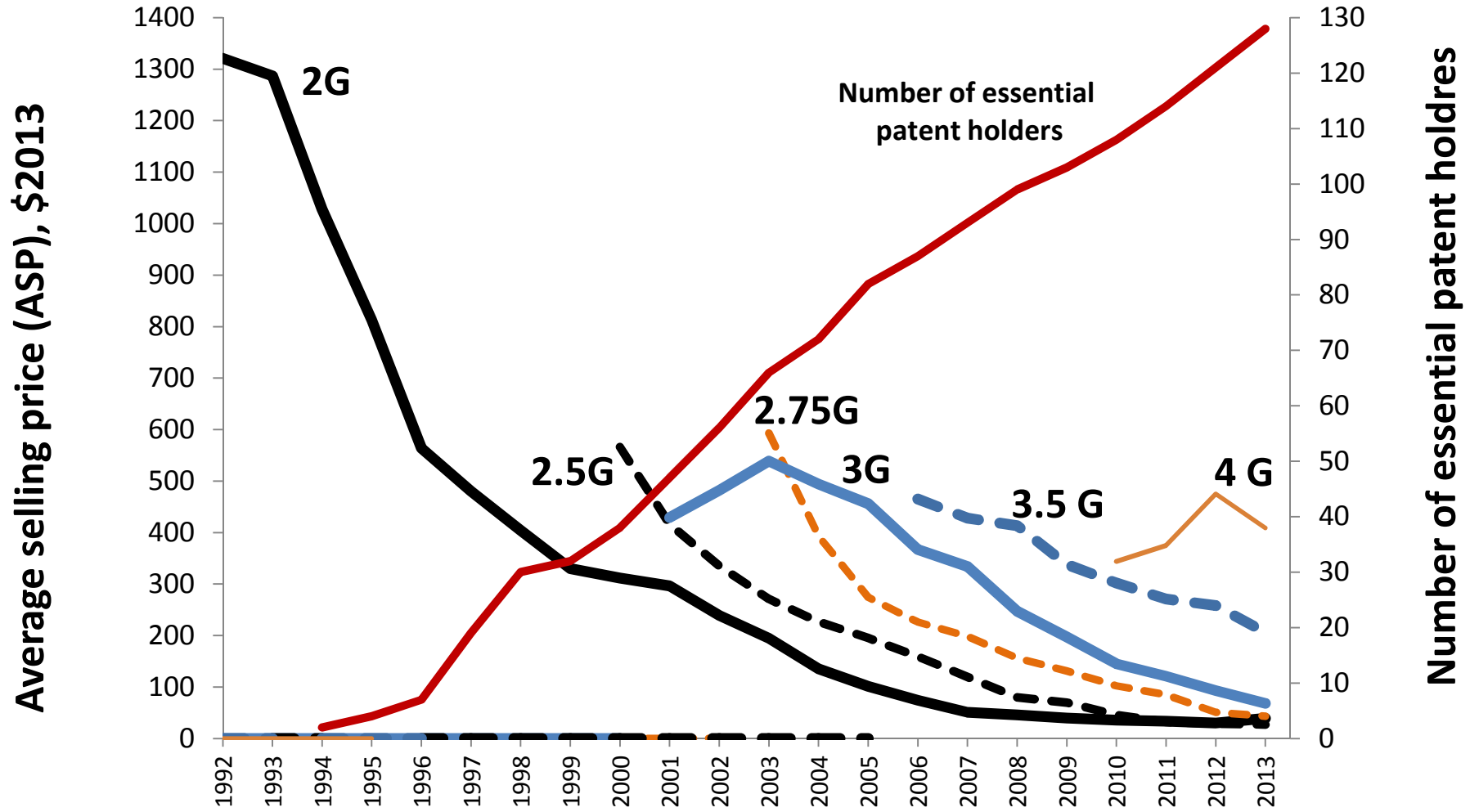
**Figure 5**  
**The mobile wireless industry value-chain**



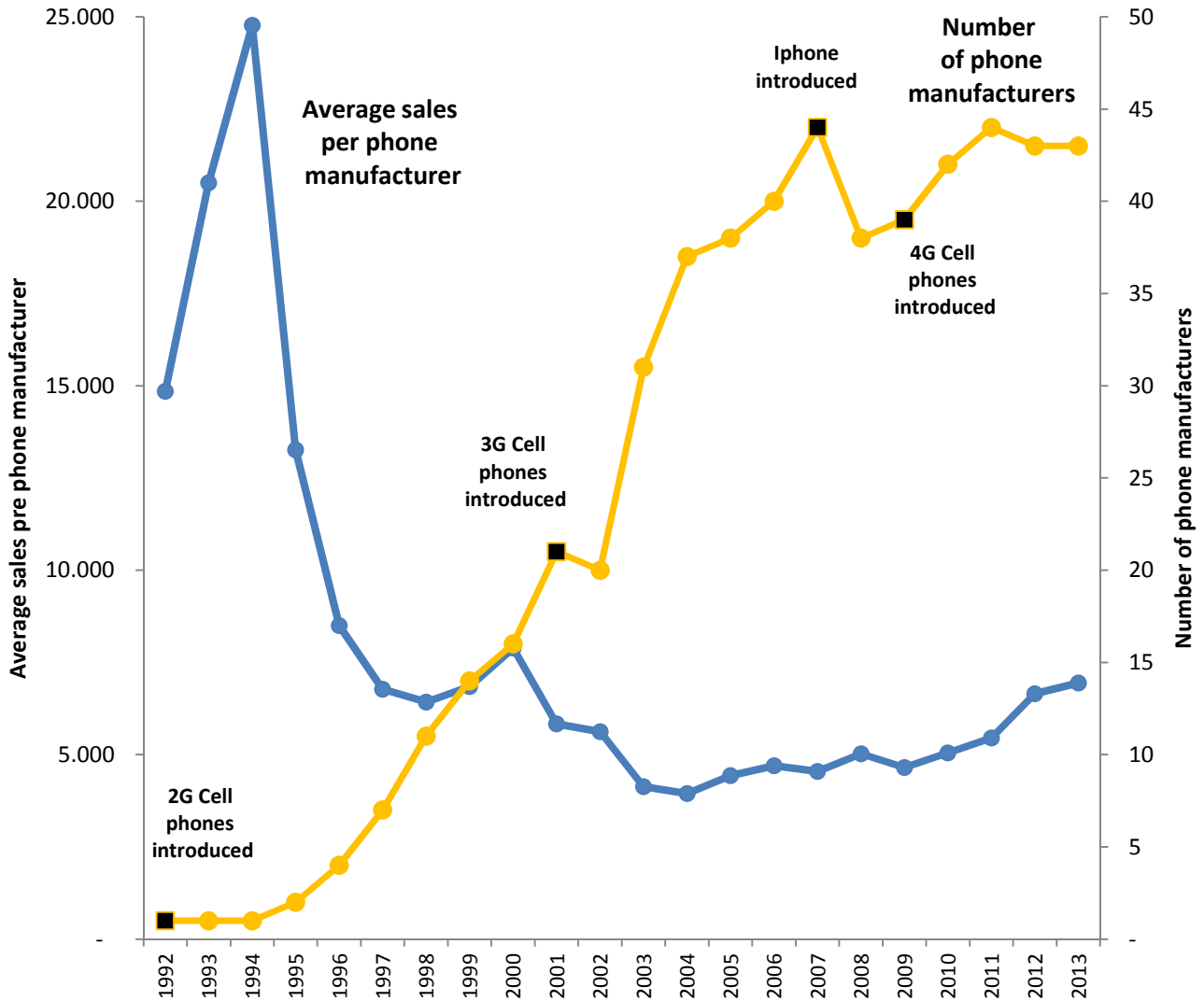
**Figure 6**  
**Annual worldwide sales of devices by technological generation, 1983-2013**



**Figure 7**  
**Average selling price of devices and number of SEP holders**

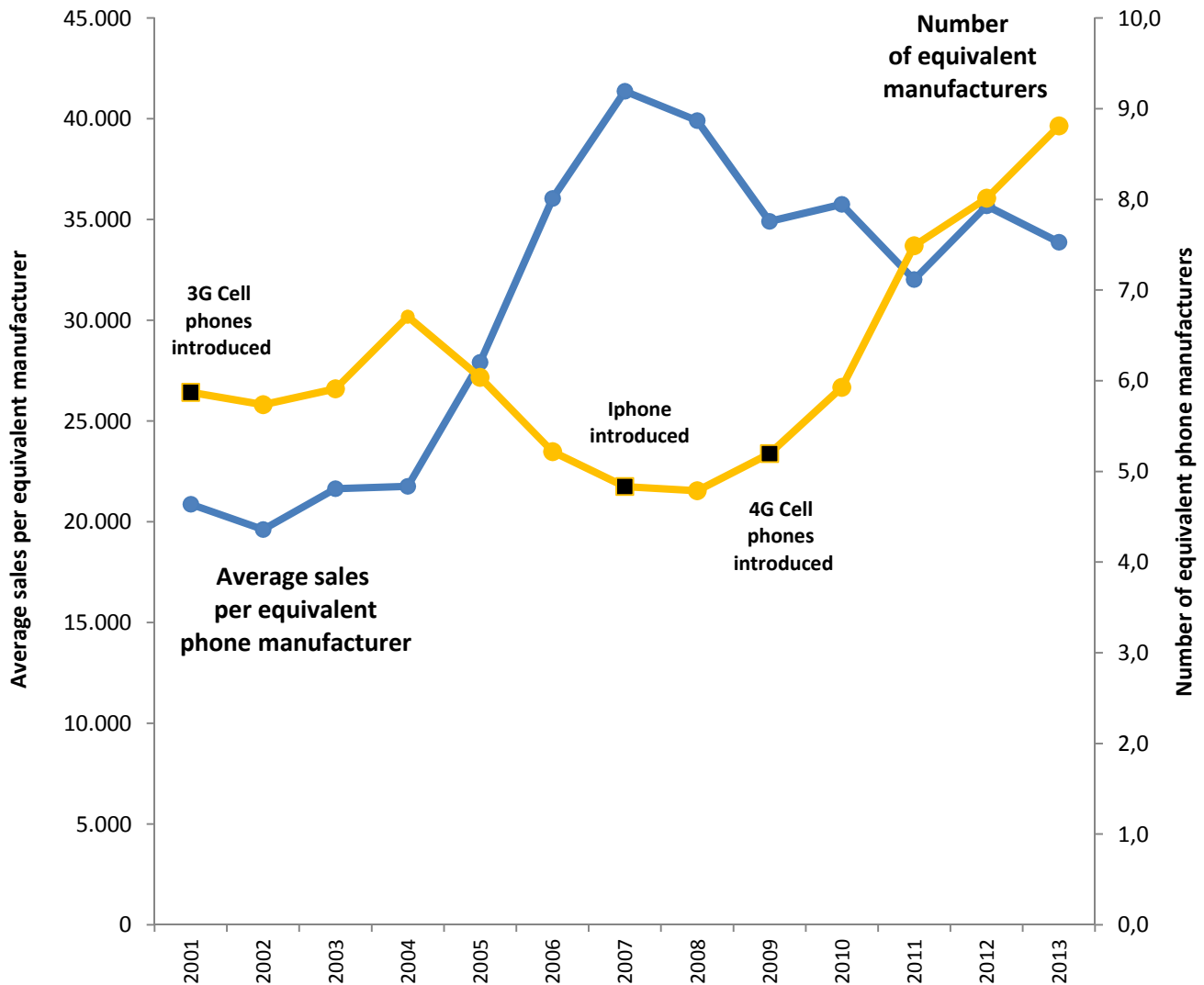


**Figure 8**  
**Number of phone manufacturers**  
**and average sales per firm**  
**(1992-2013, millions of 2013 \$)**



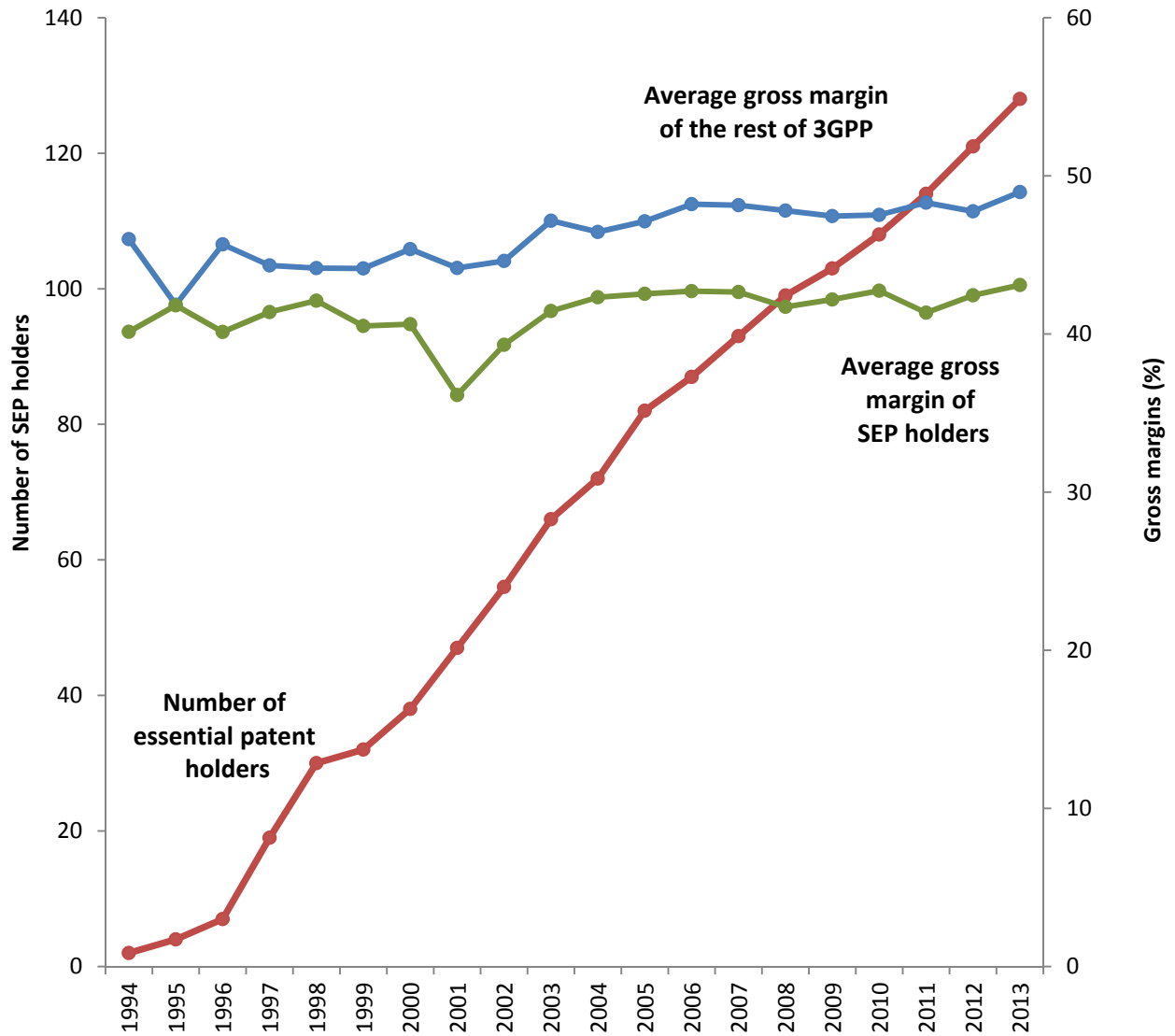
This graph shows the evolution of average sales per smartphone manufacturer. Until 2004 the number of firms grew substantially; after 2004, the number stabilized between 40 and 45. Average sales per manufacturer stabilize between 5-7 billion a year ---the number of firms is roughly proportional to market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

**Figure 9**  
**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 10**  
**Average gross margins,**  
**SEP holders ( $\geq 1$  SEP) and rest**  
**(1994-2013)**



**Figure 11**  
**Average gross margins,**  
**SEP holders ( $\geq 1$  SEP) and rest of 3GPP**  
**(device manufacturers)**  
**(1994-2013)**

