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Original article

The case of the missing royalty stacking in the world mobile wireless industry

Alexander Galetovic[1,2,3] **and Kirti Gupta**[4]

[1]Universidad Adolfo Ibáñez Santiago, Chile. e-mail: alexander.galetovic@uai.cl, [2]Hoover Institution, Stanford University, [3]CRIEP and [4]Economic Strategy, Qualcomm Inc. e-mail: kgupta@qualcomm.com

Abstract

We build an equilibrium royalty stacking model that links the number of standard-essential patent (SEP) holders with the equilibrium quantity, price and cumulative royalty. We show that all observable implications of the theory are inconsistent with the data from the world mobile wireless industry. In this industry, the number of SEP holders grew from 2 in 1994 to 130 in 2013. Royalty stacking theory predicts falling or stagnant output, rising selling prices, and rising or stagnant quality-adjusted prices. By contrast, between 1994 and 2013 worldwide yearly device sales grew 62-fold, at an average rate of 20.1% per year, and both selling and quality-adjusted prices fell fast over time. Controlling for technological generation, the real average selling price of a device fell between -11.4% and -24.8% per year. Similarly, under conservative parametrizations, royalty stacking theory predicts royalty yields, which are more than an order of magnitude larger than the observed average cumulative royalty yield charged by SEP holders in practice, which hovers between 3% and 3.5%. A theory based on Lerner and Tirole's (2015, *J. Political Econ.*, 123(3), 547–586) within-functionality competition yields observable implications consistent with the observed facts. If all the technologies protected by SEPs have meaningful substitutes that cap the royalty that any SEP holder can charge, then the cumulative royalty is independent of demand parameters in the downstream market and can be as low as the observed average cumulative royalty yield. Moreover, if the product market is competitive and technological progress is fast, then prices follow costs, quality-adjusted prices protractedly fall, and sales grow fast.

JEL classification: L1, O31, O38

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 research and development (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, thus stifling innovation.[1]

Royalty stacking is an application of the Cournot effect to industries where many firms own patents that read on the same product.[2] As Spulber (2016, 2017) 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 (2016) 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."[3] Indeed, Shapiro (2000) 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.[4] Because royalty stacking implies high margins, many authors warn that it 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.[5] And, recently, Scott Morton and Shapiro (2016) warned that royalty stacking threatens the development of the Internet of Things.

Despite being an influential theory developed by prominent academics, the royalty stacking hypothesis has not been tested systematically, and thus the evidence so far has been rather inconclusive.[6] Part of the reason for the lack of testing is that there is no systematic effort to contrast the observable implications of the theory with the data coming from actual industries. Indeed, the royalty stacking claim is based largely on a simple model with linear demand in Lemley and Shapiro (2007), who did not explore its observable implications, much less tested them against data. Subsequent authors have simply assumed that royalty stacking is a serious possibility.[7] Unfortunately, the theory and actual SEP-intensive industries have evolved in parallel and the purpose of this article is to link them.

We begin in Section 2 by examining data from a quintessential candidate industry for royalty stacking, mobile wireless. We find that the evidence looks rather inconsistent with the dire predictions of royalty stacking theorists and antitrust authorities. As shown in Figure 1, 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. Yet during the same period device sales grew fast. For example, in 1994, one manufacturer (Ericsson) sold 29 million devices. In 2013, by contrast, 43 manufacturers sold 1810 million devices, a 62-fold increase, at an average rate of 20.1% per year.

The second and related fact is that between 1994 and 2013, and controlling for technological generation, the real average selling price (ASP) of a device fell between −11.4% to −24.8% per year. Moreover, the introductory ASP of

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[1] An 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). As we will argue below, however, it is doubtful that the technologies that receive SEPs have no substitutes.

[2] Cournot (1897, ch. 9). For royalty stacking see, for example, Shapiro (2000), Lemley (2007), Lemley and Shapiro (2007), Golden (2007), Miller (2007), Denicolo *et al.* (2008), Elhauge (2008), Geradin *et al.* (2008) Sidak (2008), Schmalensee (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 (2016), Spulber (2016, 2017), Galetovic and Haber (2017), and Galetovic *et al.* (2017). See also the more general theoretical analysis of Lerner and Tirole (2004, 2015) and Spulber (2016).

[3] Many call it the "Cournot-complement effect," because in the literature the problem is usually set in a model with complementary inputs. Nevertheless, recently Spulber (2016) 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, and not by complementarity. See also Spulber (2017).

[4] See also Lerner and Tirole (2004), Lemley and Shapiro (1991), and Spulber (2016).

[5] See, for example, United States Federal Trade Commission (2011), United States Department of Justice and Federal Trade Commission (2007), and Vestager (2016) (for court cases, see Judge Robart's decision on the Motorola vs. Microsoft (2012) case, and the recent comprehensive survey by Barnett [2017]).

[6] As Layne-Farrar (2014) notes: "Certainly the theories have been developed, but the empirical support is still 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."

[7] See, for example, Lerner and Tirole (2015).

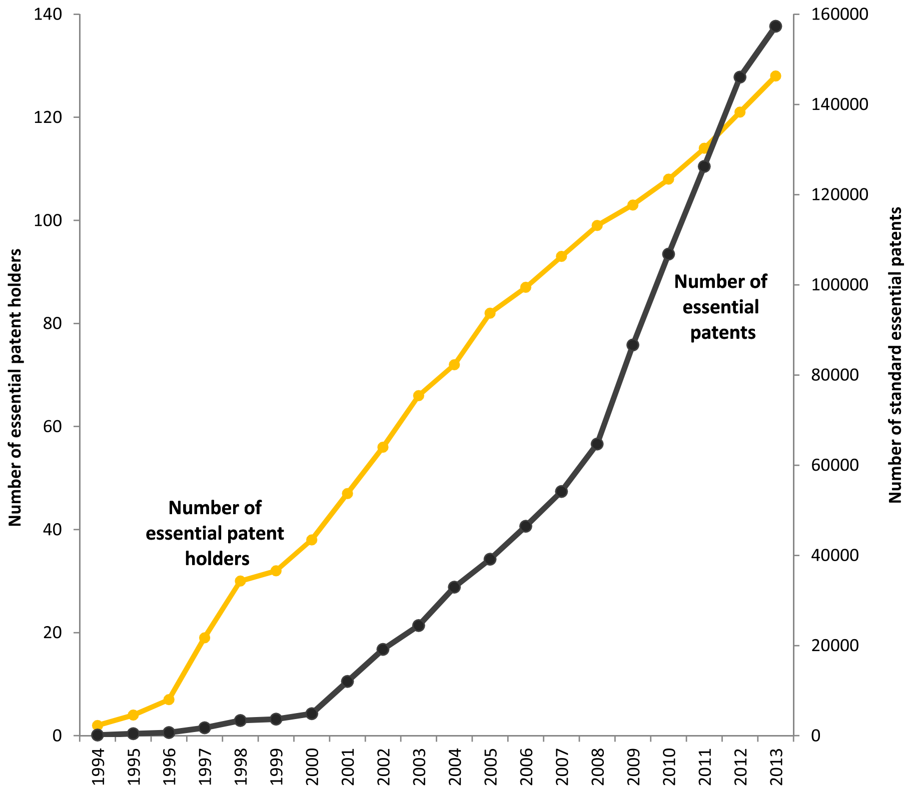

Figure 1. Number of SEPs and SEP holders (1994–2013). SEPs, standard-essential patents.

successive device generations fell, suggesting that consumers captured an increasing fraction of the value created by technological progress, confirming an earlier finding of Galetovic *et al.* (2015).[8]

The third fact is that the cumulative royalty charged in the entire value chain of the world mobile wireless industry looks rather modest. Galetovic *et al.* (2018) estimated that, since 2009, the average cumulative royalty yield—the sum total of patent royalty payments earned by licensors, divided by the total value of mobile phones shipped—hovers between 3% and 3.5%, which seems rather modest.

To contrast these facts with the observable implications of royalty stacking theory, in Section 3, we build a two-stage model where 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.

To ensure that our results are not driven by specific functional forms and assumptions about downstream market structure, our analysis is couched in terms of a family of models. 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.

Perhaps the main result is that royalty stacking reduces equilibrium output to a very small magnitude very fast, and eventually the industry 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.

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[8] In the evolution from 2G to 4G technologies, maximum download speeds increased about 12,000 times from 20 *kilo*bits per second in 2G to 250 *mega*bits per second in 4G.

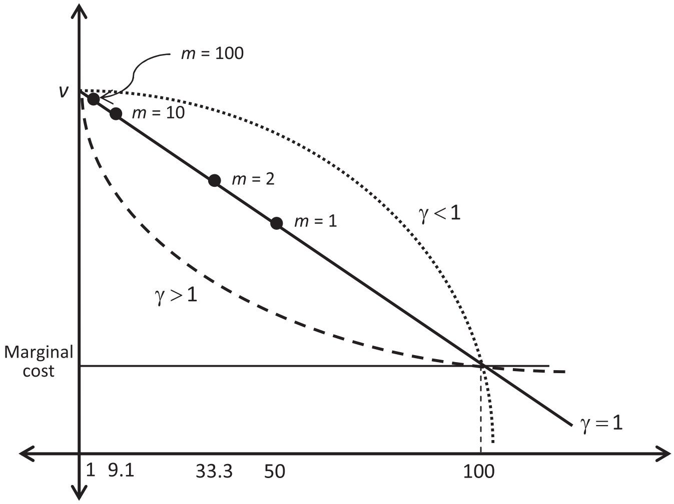

Figure 2. Royalty stacking with constant pass-through, log-concave demand.

To see why, it is helpful to use Figure 2 that plots three constant rates of pass-through, log-concave demand curves of the form

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

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, and S is a scale parameter chosen so that output equals 100 when price is equal to marginal cost.[9]

The Cournot effect hypothesis applied to SEP-intensive industries is that the technology owned by each SEP holder has no substitutes. Thus, each SEP holder is a monopoly who posts royalties non-cooperatively to maximize profits. Then, one can show that if the demand curve is linear ($\gamma = 1$) and there are m SEP 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% lower than with marginal cost pricing. And if the number of SEP holders is 100, then output would be 1—99% lower than with marginal cost pricing and 1/50th of output with one SEP holder.

As shown in Figure 2, 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: the industry nearly collapses with a modest number of SEP holders. Moreover, in an extension, we show that if simultaneously there is fast technological progress and consumer willingness to pay v rises, quantities stagnate. Thus, royalty stacking is not consistent with fast-growing sales.

The theory also predicts that the equilibrium price will rise fast with the number of SEP holders. Indeed, a modest number of SEP holders is sufficient for the cumulative royalty to become high enough to almost fully extract

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[9] That is, $100 = S(v - c)^{\gamma}$. Moreover, in this example (though not in the rest of the article), we assume that the downstream market is competitive, so with no patent rights price is equal to the unit cost of manufacturing.

consumer surplus. More important, with enough SEP holders, 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. Contrary to a commonly held belief, therefore, royalty stacking cannot be compensated by countervailing factors that offset the surplus extracted by SEP holders.

Thus, royalty stacking theory predicts falling or stagnant output, rising selling prices, and rising or stagnant quality-adjusted prices. By contrast, as we have already mentioned, between 1994 and 2013 worldwide yearly device sales 62-fold, at an average rate of 20.1% per year, and both selling and quality-adjusted prices fell fast over time. Controlling for technological generation, the real ASP of a device fell between −11.4% and −24.8% per year. Similarly, under conservative parametrizations, royalty stacking theory predicts royalty yields that are more than an order of magnitude larger than the observed royalty yield. Thus, one cannot reject the null hypothesis that there is no royalty stacking.

If theory predicts the opposite that the data show, some of its assumptions must be wrong. One key assumption of royalty stacking theory is that there are no feasible substitutes for the technologies on which SEPs read. We relax this assumption using Lerner and Tirole's (2015) concept of within-functionality competition. Within-functionality competition allows competition from alternative technologies, even after the standard has been chosen, and implies that the royalty that an SEP holder can charge is capped. 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. It departs from the literature on standards, most of which assumes that it is materially impossible to switch to a substitute technology after a standard is set.

We show that when the unconstrained best-response royalty of each SEP holder is higher than the royalty that the SEP holder can charge given within-functionality competition (i.e. all SEP holders are constrained by within-functionality competition), then the cumulative royalty is equal to the sum of the royalty caps. Thus, the cumulative royalty becomes independent of demand and supply parameters in the downstream product market. This is consistent with the fact that the average cumulative royalty yield observed in the world mobile wireless industry, which was estimated by Galetovic *et al.* (2018) in 3.4%, is at least one order of magnitude smaller than the royalty predicted by royalty stacking theory. Thus, as Galetovic and Haber (2019) argue, the fact that observed royalties are modest suggest that, contrary to the common belief, SEPs have meaningful substitutes even after standardization. Modest royalties also suggest that the costs that firms must incur to switch to another technology are not prohibitive.

In addition, we show that if the downstream market is competitive, and technological progress is fast, then prices follow costs, quality-adjusted prices protractedly fall, and sales grow fast. These observable implications coincide with the observed data from the world mobile wireless industry.

Lastly, we show that if the technology of at least one SEP holder has no substitutes, then the cumulative royalty is at least as high as the royalty that would be charged by a bundled monopoly (an SEP holder that owns all patens), and generally higher. This is inconsistent with the facts, because the royalty that would be charged by a bundled monopoly is at least an order of magnitude larger than the observed average cumulative royalty yield estimated by Galetovic *et al.* (2018).

We end with a short exploration of the theoretical reasons why SEP holders confront substitutes, despite SEPs being "essential." As Kretschmer and Reitzig (2016) show, firms invest in R&D ex ante in technologies that they later discard after joining a standard. Their theoretical analysis suggests that firms use these technologies as outside options when bargaining for the surplus created by the standard. Interestingly, the incentive to invest ex ante in substitute technologies is stronger when network externalities are stronger. When applied to SEPs and royalty stacking, their insight suggests that implementers who participate in a standard do so precisely because they have options to switch.

Our study is related to the literature on the Cournot effect. As we already mentioned, Spulber (2017) synthesizes this literature, showing 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. Indeed, the Cournot effect is, in essence, a theory about a market failure, not about input pricing with multiple suppliers in markets that work.

Our study is also related to the literature on royalty stacking. As 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.[10] 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 studies 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), Geradin and Rato (2007), Denicolo *et al.* (2008), Geradin *et al.* (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 *et al.* (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.[11] We add to this literature by showing that one cannot reject the null hypothesis of no royalty stacking in the mobile wireless industry. Indeed, all predictions of the theory are inconsistent with the data.

The rest of the article is organized as follows. Section 2 presents the facts from the world mobile wireless industry. Section 3 studies the implications of royalty stacking theory and the restrictions it imposes on observable outcomes. Section 4 shows that one cannot reject the null hypothesis of no royalty stacking, develops the theory and implications of within-functionality competition, and shows that its observable implications are consistent with the data. Section 5 concludes.

2. Some facts from the world mobile wireless industry

2.1 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.[12] Figure 3 shows the evolution of worldwide phone device sales in millions since 1994, distinguishing by technological generation (1G, 2G, 2 GPRS, 2.5G, 2.5 GPRS, 3G, 3.5G, and 4G). Also, for reference, we plot the number of SEP holders. Device sales grew very fast. As shown (barely) in Figure 3, in 1994, one manufacturer (Ericsson) sold 29 million devices. In 2013, by contrast, 43 manufacturers sold 1810 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 1 year of any given generation.

Device sales grew because prices fell and quality increased. The weighted worldwide ASP 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 at any given moment sells for higher prices, masks that quality-adjusted prices are falling faster.

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

[11] 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.

[12] See the Appendix for data sources.

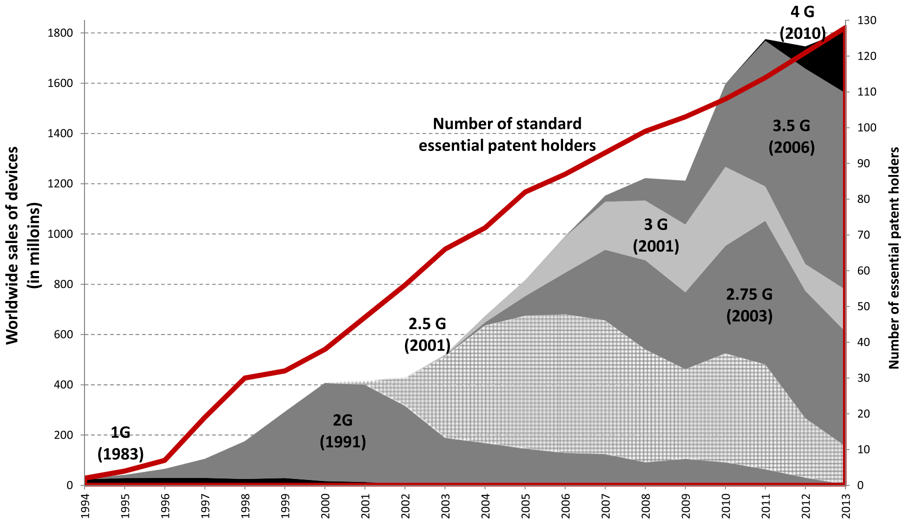

Figure 3. Annual worldwide sales of devices by technological generation, 1994–2013.

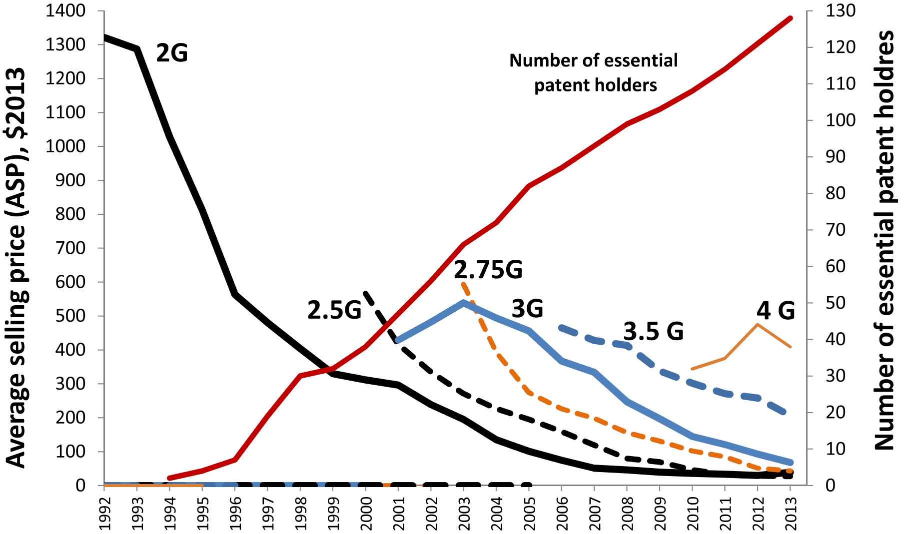

Figure 4. Average selling price of devices and number of SEP holders. SEP, standard-essential patent.

A rough way to gauge the rate of fall of quality-adjusted prices is to track the ASP of each technological generation, which we do in Figure 4.[13] As shown in the figure, the introductory price has fallen with each successive generation, despite the fact that over time quality has improved.

Figure 4 also shows that the ASP 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.

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

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

	(1) Coefficient	(2) Standard error	(3) t-value	(4) P-value	(5) Predicted price during the first year (in 2013 \$)	(6) Average annual rate of change (%)
Intercepts (α_i)						
1G	9.23	0.15	60.5	0.00	7959	−21.6
2G	−1.96	0.18	−11.2	0.00	1188	−16.6
2G (GSM)	−1.69	0.18	−9.6	0.00	1463	−21.6
2.5G	−2.53	0.19	−13.5	0.00	632	−21.6
2.5G (GPRS)	−2.64	0.19	−14.0	0.00	547	−24.8
2.75G (Edge)	−2.73	0.20	−13.8	0.00	519	−21.6
3G	−2.50	0.19	−13.1	0.00	689	−17.0
3.5G	−2.93	0.22	−13.6	0.00	480	−11.4
4G	−3.43	0.28	−12.1	0.00	354	7.6
Rate of change (β_i)						
1G	−0.216	0.010	−22.4	0.00		
2G	0.050	0.012	4.3	0.00		
2G (GSM)	0.000	0.012	0.0	0.99		
2.5G	−0.021	0.016	−1.3	0.19		
2.5G (GPRS)	−0.032	0.016	−2.0	0.05		
2.75G (Edge)	−0.028	0.021	−1.3	0.19		
3G	0.046	0.017	2.6	0.01		
3.5G	0.102	0.032	3.2	0.00		
4G	0.292	0.088	3.3	0.00		
n	124					
Groups	9					
R^2	0.972					

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

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

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

Columns 1–4 report the regression results in logs. Column 5 shows the price predicted by the regression during the first year of the respective generation, which has fallen dramatically. This confirms that quality-adjusted prices have fallen over time.

Column 6, in turn, 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 2.5G (GPRS). This is the usual pattern followed by the prices of information technology (IT) goods: prices fall fast after introduction, a combination of fast entry by competitors and learning effects that lower manufacturing costs.

2.2 Royalties

It is usually thought that royalties charged by SEP owners are not observable, because licensing agreements are confidential. Nevertheless, Galetovic *et al.* (2018) estimated the average cumulative royalty yield—the sum total of patent royalty payments earned by licensors, divided by the total value of mobile phones shipped—in the world mobile phone industry between 2007 and 2016 by exploiting the fact that licensing revenues usually are registered in licensors' financial statements.[14] They identified, with varying accuracy, 39 potential licensors in the smartphone value

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[14] See also Mallinson (2015) and Sidak (2016).

chain, including technology development companies, patent assertion entities, and patent pools, but only 29 charged royalties in 2016, running from a low of \$1.6 million to a high of \$7.7 billion, summing to \$14.2 billion in total, which compares with \$425.1 billion in mobile phone sales. It seems, therefore, that many SEP holders do not charge any royalties.

Moreover, for an expanded group of 22 licensors, which accounted for 93% of all royalty revenues in 2016, they went back to 2009 and found that the average cumulative royalty yield hovers between 3% and 3.5%. The stability of the average cumulative royalty yield over time is remarkable, given that between 2007 and 2016 sales of mobile phones the share of smartphones in total mobile phone sales increased from less than 20% to more than 95%, and total sales roughly doubled.

3. An equilibrium model of royalty stacking

3.1 The model

In this section, we study royalty stacking with a two-stage game. Our aim is to study the link in equilibrium between the number of SEP holders and observable market outcomes—quantity, price, and cumulative royalty. We now describe the model.

3.1.1 Demand

Following Genesove and Mullin (1998), the demand function, D, is

$$Q = D(p) \equiv S(v-p)^{\gamma}, \tag{1}$$

with $\gamma > 0$. Q and p have obvious meanings and S is the size of the market.[15] 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 (Figure 1). 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 $v, \gamma \to \infty$ 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

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

which implies that D is log-concave.[16] 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,

$$\frac{d\eta}{dp} = -\left(\frac{D'}{D} + p\frac{d\frac{D'}{D}}{dp}\right) = \gamma\frac{v}{(v-p)^2} > 0, \tag{3}$$

and

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

[16] 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.

$$\lim_{p\to v}\eta(p) = \gamma \lim_{p\to v}\frac{p}{v-p} = \infty. \tag{4}$$

Therefore, property (2) implies that with bounded willingness to pay, the price elasticity of demand η is increasing in p and unbounded.

Remark 1 *Our demand function is similar to the formulations used by Lerner and Tirole (2004, 2015). In our specification v is willingness to pay and is similar to their function V. In Lerner and Tirole (2004), V is an increasing function of the number of innovations; in Lerner and Tirole (2015), 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 ours, Lerner and Tirole (2004, p. 693, 2015, p. 552) assume bounded willingness to pay and their demand functions also exhibit property (2). This implies that the elasticity of demand is increasing in price and* $\lim_{p\to v}\eta(p) = \infty$ *(our properties 3 and 4).*

3.1.2 Manufacturers

Each manufacturer produces each unit of the final good at constant unit cost c and pays a linear cumulative royalty $\mathcal{R}$ per unit of output.

3.1.3 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. To simplify, we assume that the cost of licensing each essential technology is 0. Each SEP holder charges a per-unit, linear royalty r_j. Thus, $\mathcal{R} \equiv \sum r_j$ is the cumulative royalty. We assume that $v - c > 0$ to ensure that an equilibrium with production exists when $m = 1$, there is no stacking, and one SEP holder licenses all patents.[17]

Remark 3 *Lerner and Tirole (2015, p. 252) introduce a "within-functionality competition index," which caps the royalty that an 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* $r_j \leq \bar{r}_j$. *We will return to this formulation in Section 4.2.*

3.1.4 Downstream competition

Downstream competition is imperfect. We follow Genesove and Mullin's (1998) variation on Bresnahan (1989). In the symmetric equilibrium, each firm chooses its output q_i so that

$$P(Q) + \theta q_i P'(Q) = c + \mathcal{R}, \tag{5}$$

where θ 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.

3.1.5 Timing

The timing of the dynamic game is shown in Figure 5. In the first 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 second stage (competition, $t = 2$), each downstream manufacturer simultaneously sets q_i, given n and $\mathcal{R}$. Hence, in our model, the conduct parameter θ indexes the intensity of competition (see Sutton, 1991).

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[17] 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.

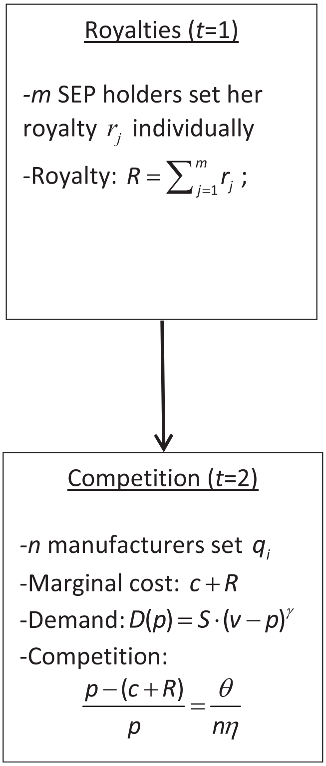

Figure 5. The royalty stacking game.

3.2 Equilibrium

3.2.1 The downstream market

We begin with the second stage of the game. Manufacturer i takes n and $\mathcal{R}$ as given and chooses his quantity to

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

Standard manipulations of the first-order condition (5) yields that the equilibrium price is

$$p=\frac{\theta v+\gamma n(c+\mathcal{R})}{\theta+\gamma n}, \tag{6}$$

and total quantity is

$$Q=S\left(\frac{\gamma n}{\theta+\gamma n}\right)^{\gamma}[v-(c+\mathcal{R})]^{\gamma}. \tag{7}$$

Note that $\frac{\partial p}{\partial n}>0$, the equilibrium price rises as n falls and concentration increases; this is the standard price–concentration relationship. Also, $\frac{\partial p}{\partial \theta}>0$, the equilibrium price rises as competition becomes less intense.

Note that the pass-through rate of royalties is

$$\frac{\partial p}{\partial \mathcal{R}}=\frac{\gamma n}{\theta+\gamma n}\leq 1. \tag{8}$$

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.

3.2.2 Royalties and royalty stacking

3.2.2.1 The Cournot effect. 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

$$\max_{r_j}\{r_j \times D(p(\mathcal{R}))\}, \tag{9}$$

where $p(\mathcal{R})$ is given by equation (6). Because unit costs are constant and the demand function is log-concave, there exists a unique, symmetric Cournot equilibrium in prices.[18] Call r_j^m SEP holder j's optimal individual royalty with m SEP holders, and $\mathcal{R}^m$ the cumulative royalty. The first-order condition is

$$r_j^m \times D'(p)\frac{\partial p}{\partial \mathcal{R}} + D(p) = 0.$$

Now in a symmetric equilibrium, $r_j^m = r^m$. Moreover, $\frac{\partial p}{\partial \mathcal{R}} = \frac{\gamma n}{\theta+\gamma n}$. Then, the first-order condition can be rewritten as

$$r^m \times \frac{D'(p)}{D(p)}p \times \frac{\gamma n}{\theta+\gamma n} \times \frac{1}{pm} + 1 = 0.$$

Hence,

$$\frac{r^m}{p} = \frac{m}{\eta}\frac{\gamma n}{\theta+\gamma n}. \tag{10}$$

Because $\mathcal{R}^m = mr^m$, it follows that

$$\frac{\mathcal{R}^m}{p} = \frac{m}{\eta}\cdot\frac{\gamma n}{\theta+\gamma n} > \frac{1}{\eta}\cdot\frac{\gamma n}{\theta+\gamma n} = \frac{\mathcal{R}^1}{p}.$$

This is the well-known Cournot effect: each SEP holder "sees" through the market demand of the final good, summarized by the price elasticity η and acts as a monopoly ignoring that her royalty reduces the profits made by the other SEP holders.[19] The consequence is that m monopolists "stack" their royalties and charge m times the Lerner margin that would be set by a monopoly SEP holder licensing all patents.[20]

3.2.2.2 Royalties. Straightforward substitutions into equation (10) and some algebra yield

$$r^m = \frac{v-c}{m+\gamma}. \tag{11}$$

Therefore,

$$\mathcal{R}^m = mr^m = \frac{m}{m+\gamma}(v-c). \tag{12}$$

Hence, as can be readily seen in equation (12):

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[18] See Vives (1999).

[19] See Shapiro (2000), Lerner and Tirole (2004, p. 695), and Proposition 4(ii) in Lerner and Tirole (2015).

[20] Shapiro (2000, p. 150) assumes perfect competition downstream. With perfect competition $\theta = 0$ and

$$\frac{\mathcal{R}_m}{p} = \frac{m}{\eta} > \frac{1}{\eta} = \frac{\mathcal{R}_1}{p}.$$

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

$$\frac{p^m - c}{p^m} = \frac{m}{\eta} > \frac{1}{\eta} = \frac{p^1 - c}{p^1},$$

which is the condition shown by Shapiro.

Result 1 (Royalty stacking and the cumulative royalty). *The cumulative royalty increases with the number of SEP holders.*

Note that the individual and cumulative royalties are increasing in $v - c$. These parameters summarize consumers' willingness to pay and manufacturing costs, and determine the economic surplus created by the downstream market. This is an important feature of royalty stacking: royalties are a function of the value of the final good to consumers (as measured by their willingness to pay v) and of the unit cost of manufacturing the final good (c). Expression (12) suggests, moreover, that as the number of SEP holders increases, they appropriate an increasing fraction of consumer surplus. As we will see next, by so doing SEP holders reduce consumer surplus and the size of the market very fast.

3.3 How harmful is royalty stacking?

How much can royalty stacking hamper the performance of downstream manufacturing? We study the relation between on the one hand, the number of SEP holders, m, and on the other hand, quantity and price.

3.3.1 Additional SEP holders do not add value

3.3.1.1 The benchmark. Our benchmark is a perfectly competitive downstream market with no royalties, which we denote with a star. In that market:

$$p^* = c, \tag{13}$$

and

$$Q^* = S(v - c))^{\gamma}. \tag{14}$$

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

3.3.1.2 Quantity. 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

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

is the equilibrium quantity. Hence,

$$\frac{Q^m}{Q^*} = \left(\frac{n\gamma}{\theta + n\gamma}\right)^{\gamma}\left(\frac{\gamma}{m+\gamma}\right)^{\gamma}. \tag{15}$$

In equation (15), the first parenthesis measures the effect of double marginalization on the equilibrium quantity. This expression disappears when the downstream market is perfectly competitive ($\theta = 0$). On the other hand, 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.

The second parentheses measure the impact of royalty stacking on quantity. It is apparent from (15) that output falls with m relative to the benchmark Q^* and that, when m is very large, the ratio $\frac{Q^m}{Q^*}$ tends to zero. The speed with which output falls depends on the curvature of the demand curve, as measured by γ.

To get an idea about how fast output falls with the number of SEP holders, Figure 6 plots ratio (15) in the vertical axis with four different values of γ, assuming that nine manufacturers ($n = 9$) compete à la Cournot ($\theta = 1$) in the downstream market. In the horizontal axis, we plot the number of SEP holders. In the vertical axis, we plot the equilibrium quantity, normalizing at $Q^* = 100$.[21]

Consider first $\gamma = 1$—the linear demand function, which Lemley and Shapiro (2007) used. As the black line in Figure 6 shows, with $m = 1$ (equivalent to a bundled monopoly) $\frac{Q^1}{Q^*} = 45$. This combines monopoly pricing by the

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[21] In 2013, the number of equivalent manufacturers in the mobile wireless device industry was 9 (see Galetovic and Gupta, 2016). (The number of equivalent firms equals $\frac{1}{\mathcal{H}}$, where $\mathcal{H}$ is the Herfindahl index; see Adelman, 1969.)

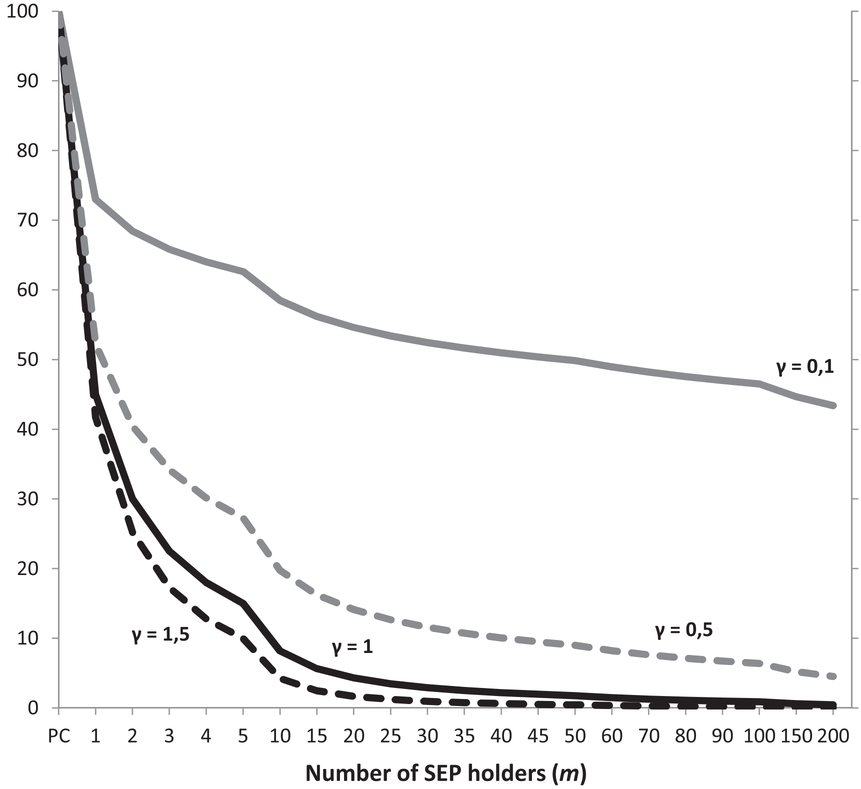

Figure 6. Equilibrium quantity and the number of SEP holders 100 = Q^*. SEP, standard-essential patent.

SEP holder, 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 $m = 10$, output falls to 8.2 relative to Q^*; with $m = 50$, output falls to 1.8; and with $m = 100$, output falls to 0.9.

Now with $\gamma = 1.5$, demand is more elastic at each price and output falls even faster as m grows. 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 γ is very small and the demand function close to vertical (e.g. $\gamma = 0.1$, as shown in Figure 6), the market nearly disappears with $m \geq 100$.[22] Hence:

Result 2 (Royalty stacking with SEP holders who add no value). *If additional SEP holders add no value (v is constant), output falls fast with m and the market collapses with a modest number of SEP holders.*

The adjective "modest" is warranted because, as shown in Figure 1, in 2013, the number of SEP holders in the world mobile wireless industry exceeded 130. Royalty stacking is not about marginal effects; on the contrary, it predicts market failure caused by posted, linear royalties.

3.3.1.3 Price and the cumulative royalty. The other side of the collapse of output is the fast increase in price. Some algebra shows that the equilibrium price–cost margin in an industry with m SEP holders is

$$p^m - c = \frac{\theta + \gamma n \cdot \frac{m}{m+\gamma}}{\theta + \gamma n}(v - c).$$

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[22] With γ close to zero, the demand curves nearly vertical but concave. Then, the equilibrium price is very close to v even with $m = 1$, 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 in the first place.

Hence, as m becomes large,

$$\lim_{m\to\infty}(p^m - c) = v - c,$$

and

$$\lim_{m\to\infty} p^m = v.$$

So as m grows eventually, p gets close to v, and no surplus is left for consumers—SEP holders extract all surplus. Similarly, recall that the cumulative royalty is

$$\mathcal{R}^m = mr^m = \frac{m}{m+\gamma}(v-c),$$

and

$$\lim_{m\to\infty}\mathcal{R}^m = v - c.$$

Therefore, as m becomes large, $\mathcal{R}^m$ tends to $v - c$, 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. Hence:

Result 3 (Royalty stacking with SEP holders who add no value). *If additional SEP holders add no value, the equilibrium price approaches maximum willingness to pay as the number of SEP holders increases. Lastly, with a large number of SEP holders, the cumulative royalty extracts almost all consumer surplus.*

3.3.2 Additional SEP holders add value

3.3.2.1 The benchmark. 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.[23]

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 substitute $m\mathcal{V}$ and ζm into equations (13), (14), and (15) to obtain our new benchmark:

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

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

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

Note that now quantity increases over time as products get better, because consumers' willingness to pay increases accordingly.

3.3.2.2 Quantity. Now if there is royalty stacking some algebra shows that in equilibrium

$$Q^m = S\left(\frac{n\gamma}{\theta+n\gamma}\right)^\gamma\left(\frac{\gamma}{1+\frac{\gamma}{m}}\right)^\gamma(\mathcal{V}-\zeta)^\gamma. \tag{16}$$

As can be seen from equation (16), as 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, if SEP holders post royalties and there is royalty stacking, sales do not increase as products improve with technological progress.

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[23] 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.

Result 4 (Royalty stacking with SEP holders who add value). *If additional SEP holders add value, output stagnates as the technology improves.*

3.3.2.3 Price and the cumulative royalty. Why does output stagnate despite the fact that successive SEP holders improve the final product? To see why, rewrite the individual royalty as

$$r^m = \frac{1}{1+\frac{\gamma}{m}}(\mathcal{V}-\zeta).$$

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

$$\mathcal{R}^m = mr^m \approx m(\mathcal{V}-\zeta).$$

Eventually, therefore, the equilibrium price will increase almost dollar by dollar with each increment to the product's value. To see this, some algebra shows that the equilibrium price is now

$$p^m = \frac{\theta(m+\gamma)+mn\gamma}{(\theta+n\gamma)(m+\gamma)}m\mathcal{V} + \frac{n\gamma}{(\theta+n\gamma)}\frac{\gamma}{(m+\gamma)}m\zeta,$$

so that

$$\lim_{m\to\infty} p^m = \lim_{m\to\infty}(m\mathcal{V}+\zeta) = \infty.$$

Thus, eventually, the equilibrium price grows *pari passu* with the increase in willingness to pay and without bound, precisely because each SEP holder extracts all the incremental surplus she creates.

Now statistical offices deal with technological progress by computing quality-adjusted prices. In this model, quality is directly measured by $m\mathcal{V}=v$. In equilibrium, therefore, the quality adjusted price is equal to

$$\frac{p^m}{m\mathcal{V}} = \frac{\theta(m+\gamma)+mn\gamma}{(\theta+n\gamma)(m+\gamma)} + \frac{n\gamma}{(\theta+n\gamma)}\frac{\gamma}{(m+\gamma)}\frac{\zeta}{\mathcal{V}}.$$

Hence,

$$\lim_{m\to\infty}\frac{p^m}{m\mathcal{V}} = \lim_{m\to\infty}\theta\left(1+\frac{\gamma}{m}\right)+n\gamma(\theta+n\gamma)\left(1+\frac{\gamma}{m}\right) = 1.$$

Eventually, therefore, the quality-adjusted price stagnates as well. This is the same result from another angle: if the quality-adjusted price is constant, the total quantity demanded also is.

We can now summarize the observable implications of royalty stacking when successive SEP holders add value:

Result 5 (Royalty stacking with SEP holders who add value). *With royalty stacking and a large number of SEP holders, the equilibrium price increases dollar by dollar with product quality and willingness to pay. The quality-adjusted price, by contrast, remains constant. This occurs because the cumulative royalty increases almost dollar by dollar with users' willingness to pay.*

3.4 It could not have been better

Our preceding analysis shows that royalty stacking theory has several observable implications on the equilibrium relation between the number of SEP holders, on the one hand, and quantities, prices, and royalties, on the other hand. Yet it is often argued that "it could have been better"—confounding factors may hide presence of royalty stacking. Thus, if observed quantities increase and prices fall in a market, some other factor may be at work compensating the effect of royalty stacking. Nevertheless, a moment of reflection suggests that there is little room for these compensating factors to change the effects of royalty stacking.

The reason is that anything that increases economic surplus downstream will raise the equilibrium cumulative royalty. To see this, note that

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

That is, whenever willingness to pay increases in \$1, or the unit cost of manufacturing falls in one dollar, SEP holders increase their royalty. It follows that when m is sufficiently 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 6. *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.*

Result 6 is important, because over time "everything else" is not constant. For example, the technological frontier may shift or manufacturing costs may fall due to exogenous factors. Nevertheless, because under royalty stacking SEP holders appropriate much of any surplus created downstream, its presence cannot be masked by exogenous trends in technology or manufacturing costs. If there is royalty stacking, it could *not* have been better.

4. The case of the missing royalty stacking

4.1 Testing the null hypothesis of no royalty stacking

We can now use the observable implications of our model to test the theory. Our conclusion is that one cannot reject the null hypothesis of no royalty stacking in the world mobile wireless industry.

4.1.1 Quantities and prices

As we have seen, royalty stacking theory delivers at least four predictions. One is that with a significant and growing number of SEP holders, equilibrium quantities are small. Moreover, when additional SEP holders add no value, output falls with the number of SEP holders; alternatively, when additional SEP holders improve the technology, output stagnates. Both predictions are inconsistent with the data from the world mobile wireless industry: 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; yet during the same period, device sales grew from 29 million devices to 1810 million devices, a 62-fold increase, at an average rate of 20.1% per year.

The second prediction of the theory is that the selling price increases with the number of SEP holders. Moreover, if technological progress improves product quality and increases consumers' willingness to pay, selling prices increase even faster, while quality-adjusted prices stagnate because SEP holders appropriate all the incremental value they create. Again, both predictions are inconsistent with the data: the introductory ASP of successive device generations fell and consumers captured an increasing fraction of the value created by technological progress.

The third prediction of the theory is that shocks that reduce the cost of manufacturing devices increase the cumulative royalty, and hence do not lower prices. Again, the predictions of the theory are inconsistent with the data: between 1994 and 2013, and controlling for technological generation, the real ASP of a device fell between −11.4% to −24.8% per year—prices follow costs.

4.1.2 The average cumulative royalty yield

As we mentioned in Section 2, Galetovic *et al.* (2018) estimated the average cumulative royalty yield—the sum total of patent royalty payments earned by licensors, divided by the total value of mobile phones shipped. In 2016, the average cumulative royalty yield was 3.4%. Moreover, it varied between 3% and 3.5% between 2009 and 2016. We now show that under reasonable parametrizations of the demand curve, the royalty yield predicted by our model is more than an order of magnitude larger than the observed royalty yield.

To see this, note that, in our model, the royalty yield is equal to $\frac{\mathcal{R}}{p}$—the ratio of the cumulative royalty and the equilibrium price. For simplicity, assume that the downstream market is perfectly competitive ($\theta = 0$). Then, some algebra shows that the royalty yield is

$$\frac{\mathcal{R}^m}{p^m} = \frac{v - c}{v + \frac{\gamma}{m} c}. \tag{17}$$

Note that the equilibrium royalty yield is a function of the maximum willingness to pay v, the unit cost of manufacturing a phone, the number of SEP holders, and γ, which measures the curvature of the demand curve.

Galetovic *et al.* (2017) followed Lemley and Shapiro (2007) assuming that the demand curve is a straight line ($\gamma = 1$) and then gauged the order of magnitude of equation (17) with data from the world mobile wireless industry. They estimated $c = \$272$, which is equal to the difference between the observed ASP of a smartphone in 2016 (\$281.60) and the cumulative average cost of patent licenses to produce a smartphone (\$9.60). They also assumed that $v = \$1,400$, the inflation-adjusted price of a 2-G phone when that technology was introduced in 1992. Lastly, they assumed a stack of 29 patent holders, the observed number of firms charging royalties in the smartphone value chain in 2016. Plugging these numbers into equation (17) yields

$$\frac{\mathcal{R}^{29}}{p^{29}} = \frac{\$1400 - \$272}{\$1400 + \frac{1}{29}\$272} = 0.80.$$

That is, royalty stacking theory predicts that 80% of the price of a smartphone should be paid to patent holders. Thus, the predicted royalty yield is more than 20 times the actual one. Indeed, even if one assumes $\gamma = 100$, which is rather absurd, the predicted royalty yield is slightly less than 50%.[24]Moreover, more realistic estimates of v would surely yield more than \$1400 and increase the predicted royalty yield. Thus, the prediction of the theory is inconsistent with the observed market data.

When theory predicts the opposite that the data show, then some of its assumptions must be wrong. The key assumptions behind the Cournot effect are that each input is technically essential and cannot be substituted and that each input monopolist posts her price non-cooperatively. Next, we examine whether relaxing these key assumptions can yield observable implications that are consistent with the facts of the mobile wireless industry.

4.2 Explaining the missing royalty stacking: within-functionality competition

We first depart from the first key assumption of royalty stacking theory—that there are no feasible substitutes for the technologies on which SEPs read. We now show that substitution can account for the observed facts.

4.2.1 Within-functionality competition

Lerner and Tirole (2015, p. 252) study standard setting organizations (SSOs) and allow for "within-functionality competition" from alternative technologies, even after the standard has been chosen. Within-functionality competition implies that the royalty that an SEP holder can charge is capped and 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. Within-functionality competition is based on the observation that patents seldom read on the functionality that a given technology achieves, only on the particular means of achieving that functionality. It departs from the literature on standards, most of which assumes that it is materially impossible to switch to a substitute technology after a standard is set.

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[24] Note, moreover, that when $\gamma = 100$, then the price elasticity of the demand for smartphones at the observed ASP would be

$$\eta = \gamma \cdot \frac{p}{v - p} = 100 \cdot \frac{\$281}{\$1,400 - \$281} = 25.$$

This is a rather incredible number, the more so considering that the demand for smartphones is derived from the demand for the services that consumers use—voice, data, video, and so on. The smartphone is only a fraction of a consumer's expenditure.

Thus, let $\bar{r}_j$ be the cap to the royalty that SEP holder j can charge without inducing substitution. Furthermore, let $\mathcal{R}^m_{-j} \equiv \sum_{i \neq j}^{m} r_j$. When setting her royalty, SEP holder j's best response is now

$$r_j^*(\mathcal{R}^m_{-j}) = \min\{\arg\max_{r_j}\{r_j \cdot D(p(\mathcal{R}^m_{-j} + r_j))\}, \bar{r}_j\},$$

where D is the downstream demand and $p(\cdot)$ is given by equation (6). This expression says that SEP holder j takes the cumulative royalty charged by the rest of the SEP holders as given and, then, charges the minimum between her unconstrained best response and the cap $\bar{r}_j$. The following proposition states a sufficient condition under which the cumulative royalty is equal to $\bar{\mathcal{R}}^m \equiv \sum_{j}^{m} \bar{r}_j$.

Proposition 1 *Let* $\bar{r}_j < \frac{v-c}{m+\gamma}$ *for all* j. *Then,* $r_j^* = \bar{r}_j$ *for all* j.

Proof Let $\bar{\mathcal{R}}^m_{-j} \equiv \sum_{i \neq j}^{m} \bar{r}_i$. We check that $\text{argmax}_{r_j}\{r_j \cdot D(p(\bar{\mathcal{R}}^m_{-j} + r_j))\} > \bar{r}_j$ under the hypothesis. Note that by hypothesis, $\sum_{i \neq j}^{m} \bar{r}_j < (m-1)\frac{v-c}{m+\gamma}$. Moreover, it can be easily shown that royalties are strategic substitutes. Hence, because $\bar{\mathcal{R}}^m_{-j} < \mathcal{R}^m$,

$$\arg\max_{r_j}\{r_j \cdot D(p(\bar{\mathcal{R}}^m_{-j} + r_j))\} > \arg\max_{r_j}\{r_j \cdot D(p(\mathcal{R}^m + r_j))\} = \frac{v-c}{m+\gamma} > \bar{r}_j.$$

This establishes the result. ■

Note that if Proposition 1 holds, the cumulative royalty depends only on the royalties that substitutes impose. Thus, competition from alternative technologies brakes the link between royalties, on the one hand, and downstream market cost and demand parameters, on the other hand. Moreover, if competition from substitute technologies is intense, the cumulative royalty charged by SEP owners will be modest, as they are in the world mobile wireless industry.

One should note that the assumptions in Proposition 1 are quite restrictive. In particular, all technologies in the standard must face intense competition from a substitute technology. By contrast, if one or more SEP holders own technologies with no substitutes—that is technologies that are technically essential—then the cumulative royalty exceeds the royalty with a bundled monopoly, as the following proposition shows.

Proposition 2 *Assume that SEP holders* $1, 2, \ldots, h$ *own technologies with no substitutes and that SEP holders* $h+1, h+2, \ldots, m$ *own technologies with substitutes such that in equilibrium* $\bar{r}_j = \min\{\text{argmax}_{r_j}\{r_j \cdot D(p(\mathcal{R}^m_{-j} + r_j))\}, \bar{r}_j\}$, *for all* $j > h$. *Then, in equilibrium:*

i. *Each SEP holder* $1, 2, \ldots, h$ *charges a royalty equal to*

$$r = \frac{v-c}{h+\gamma} - \frac{1}{h+\gamma} \cdot \sum\nolimits_{j=h+1}^{m} \bar{r}_j. \tag{18}$$

ii. The *cumulative royalty equals*

$$\mathcal{R}^h = \frac{h}{h+\gamma}(v-c) + \frac{\gamma}{h+\gamma} \cdot \sum\nolimits_{j=h+1}^{m} \bar{r}_j. \tag{19}$$

Proof Note that each SEP holder $1, 2, \ldots, h$ solves

$$\max_{r_j}\left\{r_j \cdot S\left(v - \frac{\theta v + \gamma n(c + \mathcal{R}^m_{-j} + r_j)}{\theta + \gamma n}\right)^{\gamma}\right\}.$$

Solving for the first-order condition yields

$$(1+\gamma)r_j = v - c - \mathcal{R}^m_{-j}. \tag{20}$$

Now in a symmetric equilibrium, all SEP holders $1, 2, \ldots, h$ set the same royalty $\tilde{r}^h$ in equilibrium. Hence, equation (20) can be rewritten as

$$(1+\gamma)\tilde{r}^h = v - c - (h-1)\tilde{r}^h - \sum\nolimits_{j=h+1}^{m} \bar{r}_j,$$

which yields equation (18) after some simple manipulations. To obtain equation (19), just add up the individual royalties.■

Proposition 2 shows that when h SEP holders own technologies that have no substitutes, the cumulative royalty is equal to the cumulative royalty that would be charged by h SEP holders plus the capped royalties of the rest of the SEP holders. This implies that if the technology of at least one SEP holder has no substitutes, the cumulative royalty is at least as high as the royalty that would be charged by a bundled monopoly.

Nevertheless, as we have already seen, bundled monopoly or joint-profit maximization cannot explain the observed data in the world mobile wireless industry. Thus, as Galetovic and Haber (2019) argue, the fact that observed average cumulative royalty yields are modest suggests that, contrary to a common belief, *all* technologies protected by SEPs have meaningful substitutes even after standardization. Modest royalties also suggest that the costs that firms would incur by switching to another technology are not prohibitive.[25]

4.2.2 The observable implications

Can within-functionality competition account for the observed facts in the world mobile wireless industry? The answer is yes, provided that the downstream market is competitive.

To see that a competitive downstream market yields predictions that are consistent with the data, note that with within-functionality competition, the equilibrium price is

$$p = c + \bar{\mathcal{R}}^m.$$

Thus, as in any competitive markets, the equilibrium price depends on costs but not on the parameters of the demand curve. The equilibrium quantity is then

$$Q = S[v - (c + \bar{\mathcal{R}}^m)]^\gamma.$$

Thus, with fast technological progress that increases willingness to pay v, output grows fast in equilibrium and without bound. Lastly, note that

$$\lim_{v\to\infty} \frac{p}{v} = \lim_{v\to\infty} \frac{c + \bar{\mathcal{R}}^m}{v} = 0.$$

Therefore, the quality adjusted price protractedly falls.

Competition downstream is necessary to account for the protracted fall of the quality-adjusted price. To see why, note that with imperfect competition downstream

$$p = \frac{\theta v + \gamma n(c + \bar{\mathcal{R}}^m)}{\theta + \gamma n}.$$

Hence,

$$\lim_{v\to\infty} \frac{p}{v} = \lim_{v\to\infty} \frac{\theta + \frac{\gamma n(c+\bar{\mathcal{R}}^m)}{v}}{\theta + \gamma n} = \frac{\theta}{\theta + \gamma n}.$$

With imperfect competition, the equilibrium price depends on consumers' willingness to pay, and so the quality-adjusted price eventually hits a lower bound.

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[25] Lerner and Tirole (2015) call this the putty or competitive environment.

4.2.3 Where do substitute technologies come from?

We end with a short exploration of the theoretical reasons why SEP holders confront substitutes, despite SEPs being "essential." The key puzzle, which is addressed by Kretschmer and Reitzig (2016), is why would firms invest in substitute technologies that will be made redundant by standardization. On the contrary, standardization should foster specialization in R&D to prevent wasteful duplication.

Kretschmer and Reitzig's theoretical analysis suggests that firms use these technologies as outside options when bargaining for the surplus created by the standard. Thus, substitute technologies are endogenous to the fact that everybody anticipates that eventually, SEP holders and manufacturers will bargain for royalties. The surprising empirical fact, however, is that observed royalties are considerably lower than the royalties and margins that would emerge if SEP holders and manufacturers maximize joint profits.

Interestingly, the incentive to invest ex ante in substitute technologies is stronger when network externalities are stronger. The economics is that, as Kretschmer and Reitzig (2016) show, the differential value of outside options increases with stronger network externalities. When applied to SEPs and royalty stacking, their insight suggests that in equilibrium, implementers who participate in a standard do so precisely because they have options to switch.

4.3 An alternative explanation for the missing royalty stacking

4.3.1 The Cournot effect

The second key assumption of royalty stacking theory is that each SEP holder independently posts a royalty (see Spulber, 2016, 2017). We now show that relaxing this assumption is not enough to generate observable implications that are consistent with the facts.

4.3.1.1 Bargaining for royalties. Spulber (2017) studies a two-stage model in which each complementary input monopolist offers a supply schedule and then bargains for the input price with manufacturers. He shows that there is a unique weakly dominant strategy equilibrium, which attains the joint-profit-maximizing outcome—output equals that of a bundled monopoly. Thus, bargaining substitutes for posted prices and eliminates the Cournot effect.

The economics of the result is that when an input monopolist chooses its maximum quantity before bargaining for the input price, her weakly dominant strategy is to set it equal to the bundled monopoly quantity. As Spulber (2017) notes, in equilibrium every input monopolist understands that her offer controls the market outcome at the margin, precisely because inputs are perfect complements. In this way, suppliers coordinate non-cooperatively in equilibrium to license enough units to implement the joint-profit-maximizing output and the Cournot effect disappears.

4.3.1.2 The inverse Cournot effect. Another solution to royalty stacking exploits the so-called "inverse Cournot effect." In an intriguing recent study, Llobet and Padilla (2019) show that, 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 stimulate litigation against weak patent portfolios. This "inverse Cournot effect" partially blocks royalty stacking and ensures that, in equilibrium, the cumulative royalty is closer to the bundled monopoly royalty but still higher.

4.3.2 Do SEP holders and manufacturers maximize joint profits?

While both mechanisms eliminate or moderate royalty stacking, one must ask whether their key prediction—SEP holders implement the bundled monopoly output, which maximizes joint profits—agrees with the observed data. The answer is no.

We first note that the theory predicts that sum of the average cumulative royalty yield and the downstream margin of the marginal manufacturer must equal the total margin with a bundled monopolist. Now if the downstream market is perfectly competitive ($\theta = 0$), the Lerner margin with a bundled monopoly is

$$\frac{p^1 - c}{p^1} = \frac{v - c}{v + \gamma c}. \tag{21}$$

The prediction of the theory is that SEP holders and downstream manufacturers will split this margin in bilateral bargaining without affecting the total quantity sold.

As with royalty stacking, we can use actual market data and the theory to predict the margin (21). If the demand curve is a straight line ($\gamma = 1$), then

$$\frac{v-c}{v+c} = \frac{\$1400 - \$272}{\$1400 + \$272} = 0.67.$$

Therefore, the theory predicts that two thirds of the price of a smartphone will accrue to SEP holders and downstream manufacturers in the form of a monopoly rent.

Nevertheless, Galetovic *et al.* (2018) show that, in 2016, most smartphone manufacturers made almost no profits—the margin of the marginal smartphone manufacturer was effectively zero.[26] As with royalty stacking, the royalty yield predicted by our model is more than an order of magnitude larger than the observed average cumulative royalty yield.

The joint-profit maximization prediction is also at odds with the behavior of quality adjusted prices over time. To see this, recall that, in our model, the quality adjusted price is

$$\frac{p}{v} = \frac{c}{v} + \frac{1}{1+\gamma}\left(1 - \frac{c}{v}\right).$$

Over time, the quality-adjusted price falls when c falls or v increases, but if quality can grow almost without bound, then

$$\lim_{v\to\infty} \frac{c}{v} + \frac{1}{1+\gamma}\left(1 - \frac{c}{v}\right) = \frac{\gamma}{1+\gamma}.$$

Thus, in the long run, the quality-adjusted price stagnates, an observable implication, which is contrary to the evidence.

5. Conclusion

Why write a paper about a theory whose observable implications are at odds with the facts? Why not go straight into a theory that explains what we observe? The main reason is that royalty stacking in IT industries remains an influential theory. Indeed, 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.[27] And, at the very least, royalty stacking and bundled monopoly are thought to be meaningful benchmarks to study and theorize about SSOs and SEP-intensive industries. Thus, an explanation of the observed facts in industries that are thought to be affected by royalty stacking must start by carefully stating the observable implications of the theory and then contrasting them with the data. Given the state of the debate on SEP-intensive industries, one can proceed to search for alternative theories only after establishing a clear disconnect between royalty stacking theory and observed facts.

In this article, we have shown that royalty stacking is a theory about declining or stagnant industries. By contrast, as Galetovic *et al.* (2015) have shown, SEP-intensive industries in general, and the world mobile wireless industry in particular, have thrived and grown fast for decades on end. The disconnect between predictions and the data suggests that the theory should be abandoned—it has little to say about SEP industries.

We have shown that a theory based on Lerner and Tirole's (2015) within-functionality competition can account for the observed facts. If all the technologies protected by SEPs have meaningful substitutes that cap the royalty that any SEP holder can charge, the product market is competitive, and technological progress is fast, then prices follow costs, quality-adjusted prices protractedly fall, and sales grow fast.

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[26] As Galetovic *et al.* (2018) show, in 2016, the average profit margin of smartphone manufacturers was equal to 11.8% of the ASP of a smartphone. Nevertheless, about 80% of industry profits accrued to Apple and the rest to Samsung. Most other manufacturers made no profits.

[27] 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).

Following Kretschmer and Reitzig (2016), future research should aim to understand where substitute technologies come from. Furthermore, future research may look critically at the standard assumption that technology substitution is not feasible after standardization. Lastly, future research may aim to understand the determinants of the equilibrium level of royalty yields.

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Appendix

SSOs and SEPs in the mobile wireless industry

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 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 and operate on networks built and owned by different companies. Moreover, smartphone A can 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).[28] 3GPP was formed in 1998 to develop a common wireless cellular system for Europe, Asia, and North America. It brought together seven telecommunication SSOs and is responsible for generating the standards endorsed by the member SSOs. One of the seven SSOs, the European Telecommunications Standards Institute (ETSI), is in charge of the day-to-day management of 3GPP. Most firms participating in 3GPP are members of ETSI. Membership in 3GPP is voluntary (i.e. any firm can become a member), and members choose the technologies that become standards by consensus or by majority voting. Nearly 500 organizations participated in the development of these standards. Between 2005 and 2014, they spent around 3.5 million person-hours in around 850 working meetings.

In the evolution from 2G to 4G technologies, maximum download speeds increased about 12,000 times from 20 *kilo*bits per second in 2G to 250 *mega*bits per second in 4G. Standards also allow specialization. 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.[29] 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

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[28] Baron and Gupta (2018) describe and explain the process of 3GPP standard setting.

[29] Some standards setting organizations produce open standards, that is participants forfeit their intellectual property rights when contributing a technology into the standard, while others produce entirely proprietary standards, that is standards controlled by a single firm or a group of entities.

interested party on "fair, reasonable and non-discriminatory terms" (FRAND).[30] 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 1 shows the time series of the number of SEPs and the number of firms owning these SEPs. During the last 20 years, the number of SEP holders for 3G and 4G standards grew from 2 in 1994 to 130 in 2013 and the number of SEPs rose from fewer than 150 in 1994 to more than 150,000 in 2013. The number of SEPs, or complementary inputs for producing mobile wireless products, and the number of firms owning SEPs have been increasing over time.

Data description

SEPs and SEP owners

We use patent declaration data collected from the 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 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; and (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. an US patent) and then obtain patents for the same invention in other jurisdictions (e.g. a patent in the European Union, JP patent). 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.

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 (2018). This includes a historical list of 3GPP members, that is 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 to 2014. There is a difference between membership and meeting attendance. Firms that are members have voting rights toward 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, 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 were 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 (2018) 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

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

Administration). 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.

Market data

We collected information on the prices of devices, the number of devices sold, and the type of devices sold.

Two data sources were used to collect this information. Data published by Strategy Analytics were used for the number of devices sold, the ASP of a phone and volume of devices sold from 1994 to 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. Information on all devices released from 1994 to 2013 was collected from www.gsmarena.com. This is a publicly available data source that provides information on device manufacturers, its specification, and the date the product was released.