DEPARTMENT OF FOOD AND RESOURCE ECONOMICS
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IFRO Working Paper

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2017 / 04

IFRO Working Paper 2017 / 04

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JEL-classification: D63, K2, L3, L44

Published: April 2017

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A Welfare Economic Interpretation of FRAND*

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April 23, 2017

Abstract

Setting an industry-wide standard is crucial for information and communication technologies for interoperability, compatibility and efficiency. To minimize holdup problems, patent holders are often required to ex-ante commit to licensing their technologies under Fair, Reasonable and Non-Discriminatory (FRAND) terms. Yet, there is little consensus, in both courtrooms and industries, on the exact meaning of FRAND. We propose a welfare economic framework that enables a precise distinction: *fairness* in the distribution of royalty payments among patent users, and *reasonableness* in setting the size of the compensation to the patent holder, where both the size and the distribution of payments are determined in a *non-discriminatory* way making sure that similar firms are treated similarly. We illustrate our approach in various classic models from industrial organization, and discuss further potential applications.

JEL Classification: D63, K2, L3, L44

Keywords: FRAND-licensing, Fair royalties, Standard setting, Patent, Shapley value

*We thank Jens Gudmundsson and Jingyi Xue, as well as seminar participants at Korea Institute of Advanced Studies for comments on earlier versions of the paper. Ko acknowledges financial support from NUS Academic Research Grant. Hougaard gratefully acknowledges financial support from the Isaac Manasseh Meyer Fellowship.

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1 Introduction

The Problem and Contribution: Setting an industry-wide standard is crucial for information and communication technologies for reasons of interoperability, compatibility and efficiency. However, once the standard has been set, a serious holdup problem arises as the patent holders now have substantially more bargaining power over licensing terms. To avoid opportunistic behaviors, Standard Setting Organizations (SSO's) require patent holders to commit to licensing their technology under Fair, Reasonable and Non-Discriminatory (FRAND) terms (Lerner and Tirole, 2014).[1] Yet, the exact meaning of FRAND is ambiguous and various methods have been used with different results (Geradin, 2013). Because of the vague notion of FRAND, there has been much controversy in both courtrooms and industries regarding licensing terms. While previous studies in the legal and economics literature discuss various interpretations of FRAND, there is little consensus on how to make a precise definition of FRAND. Moreover, the literature often use FRAND and RAND interchangeably, with some authors even claiming that there is no distinction (e.g., Carlton and Shampine 2013). In this paper, we suggest to embed a formal definition of FRAND within a welfare economic framework. This enables a precise distinction between *fairness* in the distribution of royalty payments among patent users, and *reasonableness* in setting the size of the compensation to the patent holder, where both the size and the distribution of payments are determined in a *non-discriminatory* way making sure that similar firms are treated similarly.

A precise definition of FRAND is important both for academic discussion and for real world application in courtrooms. For instance, the patent *hold-out* problem can been seen as the result of vaguely defined licensing terms: under the FRAND commitment any patent user is only bound by the FRAND royalty; therefore if the upper bound of FRAND is unclear, users may deliberately choose not to seek the license and exploit the legal uncertainty in court, which seriously reduces the incentive to innovate. Another benefit from a more precisely defined notion of FRAND is to address *royalty stacking*: without a precise definition of FRAND, patent holders can reasonably ask for the ex-ante incremental value of their technology, which may exceed the economically viable value of the standard and thereby defeat the standard setting purpose.

To illustrate our approach, consider several firms forming a coalition that pools their

[1] The notion of FRAND originates from different Standard Setting Organizations (SSO's) such as European Telecommunications Standard Institute (ETSI) and the Institute of Electrical and Electronics Engineers (IEEE). See the further discussion on the history of FRAND in Carlton and Shampine (2013) and Ménière et al. (2015).

patents (technologies) to form a standard. Since each firm has already agreed to form the coalition, a reasonable compensation to each patent holder is based on the incremental contribution of the patent to the coalition as a whole. Subsequently, to fix royalty payments we need to find a fair division of the compensation to each patent holder among all coalition members (including the patent holders themselves). Setting a fair royalty payment, we suggest proportional sharing relative to a given firm-specific liability index for each individual patent in the pool. This liability index is based on firm-specific incremental benefits from having access to various subsets of the available patents. As one example of a compelling liability index we suggest to use the Shapley value of the naturally induced cooperative game in patents for each firm in the coalition. As such, we make a clear distinction between using social value (incremental coalition value) when determining the reasonable size of the compensation to each patent holder, and using private values (average incremental firm-specific value) when determining the fair royalty payment for each implementer. Moreover, we obtain a clear definition of the fee that a patent holder should charge itself: a question posed, and analyzed, by Swanson and Baumol (2005).

The literature seems to agree that a reasonable royalty implies that compensation does not include any holdup-value (Carlton and Shampine 2013). More specifically, a reasonable royalty should "reflect what would happen as a result of well-informed ex ante technology competition " (Swanson and Baumol, 2005; Lemley and Shapiro, 2013). There also seems to be some degree of consensus that "non-discriminatory" means that royalty does not depend on the identity of licensee, but may allow price discrimination based on quantity (Gilbert 2011, Sidak 2013). Our suggested definition is in line with the literature on both these issues.

However, agreeing on what is a fair royalty is more problematic. The literature does not have a clear definition of fairness, so it is commonly mixing RAND and FRAND as pointed out by U.S. Department of Justice and Patent & Trademark Office (2013) and Sidak (2013). Our paper intends to capture fairness in the distribution of royalty payments by a mixture of proportionality with respect to a firm-specific characteristic, i.e., the firm's liability index for each patent, and Shapley's idea of fairness as average incremental contribution of each available patent for each firm (Shapley, 1953). Note that the Shapley value has been criticized in the literature for two important drawbacks: computational complexity and for rewarding inferior substitutable patent holders (and even non-patent holders). Our approach does not suffer from any of these drawbacks as we shall apply the Shapley value in a totally different context than what has previously been suggested in the literature (see e.g., Layne-Farrar et al. 2007).

To illustrate our conceptual framework in standard setting licensing (Lerner and Tirole, 2015), we apply our approach to several well-known models in industrial organization. First, we consider horizontal markets where every firm engage in Cournot competing in the same market (homogeneous products) or related markets (heterogeneous products).[2] When firms are symmetric, our FRAND liability implies equal sharing, i.e., firms pay identical royalty fees. Sidak (2013) mentions two rules: (a) *top down* that equates per unit royalty to the product of the profit margin and the fraction of incremental contribution of patent to the value of standard, (b) *proportional contribution* that equates per unit royalty to the product of the price of the final product and the fraction of incremental contribution of patent to the value of standard. Our approach coincides with the top down rule and hence differs from the proportional contribution by the factor of relative markup. However, dropping the symmetry assumption, our approach is very different from the two rules since they relate to the total profit ratio while our approach relates to marginal profits, taking the differences into account. Therefore, our approach coincides the top down rule only when all technologies are truly essential. When firms produce heterogeneous goods, our FRAND royalty depends on the market structure and firm characteristics. Our rule leads to equal sharing only when firms are symmetric and face symmetric demand.

Second, we consider vertical markets where upstream firms are indispensable to value creation and downstream firms compete in Cournot markets. FRAND royalties depend on the market structure. When downstream firms produce homogenous goods, more upstream firms reduce the FRAND royalty of all firms; however, more downstream firms will increase the royalty of upstream firms, but reduce the royalty of downstream firms. In the heterogeneous good markets, the latter effect is rediscovered. Moreover, when downstream competition increases, the upstream firm gets a larger share of the compensation, but interestingly when markets become more elastic, the liability of the upstream firm is reduced.

Our approach is also useful for a planner/regulator who is interested in finding fair and reasonable compensations to promote industry-wide cooperation. Examples include patent pool (Lerner and Tirole, 2004), research joint venture (Katz, 1986), and platform market (Church and Gandal, 1992; Rochet and Tirole, 2003).

The Literature on FRAND: Before the notion of FRAND commitment, rules to determine

[2]In the online appendix, we show that similar results can be obtained if firms engage in Bertrand competition.

reasonable royalties for patent infringement has been established in US courtrooms. The most prominent case is *Georgia-Pacific v. United States Plywood* in 1970. The so-called Georgia-Pacific factors, details 15 different factors, that still serve as an important reference for court cases.[3] However, this does not provide a precise definition of a reasonable royalty (Layne-Farrar et al., 2007; Geradin, 2013; Ménière et al., 2015), and accordingly various simple rules has been proposed.[4] One notable example is the *numeric proportionality rule* that distributes royalties according to the number patents essential to the standard. This has been proposed in several cases against Qualcomm in EU.[5] This has also been used in patent pools (Layne-Farrar and Lerner, 2011). Although it reduces transaction costs, it seems neither fair nor reasonable.[6]

Currently, US courts adopt the following three approaches to determine FRAND royalties (Leonard and Lopez, 2014).[7] First, the **bottom-up approach**, as in *Microsoft v. Motorola*. It focuses directly on ex-ante incremental value of the patent. One identifies the set of alternatives available and then determines the incremental value of the patent (Leonard and Lopez, 2014). Second, the **top-down approach** as in *In re Innovatio IP Ventures, LLC Patent Litigation.* It first determines the aggregate royalty burden that can be charged for all patent holders, and then an apportionment of the aggregate burden is the FRAND royalty (Sidak, 2013; Leonard and Lopez, 2014; Baron and Schmidt, 2016). Third, the **comparable approach** uses comparable market transactions as reference point. While this may be easy in some situations, it is generally hard to find appropriate benchmarks (Leonard and Lopez 2014; Geradin 2016), and it does not always follow the principle of FRAND, especially when the reference does not follow the same principle.

[3]For example, one factor requires the royalty to be an outcome from hypothetical arm's length negotiation at the time of infringement, and one factor considers opinion testimony of qualified experts.

[4]Besides simple rules, a wide range of methodologies has been proposed. For example, Sidak (2013) suggests that FRAND rate can be determined as equal weighted of mid-points of the bargaining ranges based on each of 15 Georgia-Pacific factors. Finding bargaining ranges may be feasible for patent infringement case as it usually involves one patent holder and one infringer. However, it may be a challenging task for standard setting as it involves a large number of patent holders, implementers and patents.

[5]In 2005, six firms in the mobile phone industry (Texas Instruments, Broadcom, Nokia, Panasonic, NEC and Ericisson) filed complaints to EU that Qualcomm violated FRAND licensing term (Brooks and Geradin, 2011). In 2006, Nokia proposed to European Telecommunications Standard Institute (ETSI) that FRAND should incorporate numeric proportionality (Geradin, 2013).

[6]Numerical proportional is fair only if all patents are created equal (Swanson and Baumol, 2005). However, patents are usually heterogeneous, and thus this rule in general is unfair. Firms have strong incentive to artificially bolster their portfolio by minor innovations or splitting patents.

[7]Courts in European jurisdictions prefer the market approach. They focus on making the bargaining environment under FRAND-compliance. While this approach is flexible, a wide span of licensing term would be qualified to pass the FRAND test (Baron and Schmidt, 2016).

Since our approach relates to specific market structures it makes the comparable approach virtually impossible. We combine the top-down, and the bottom-up approach: royalties are found sharing the aggregate compensation, but our fairness requirement, in the form of a separability requirement (called additivity), implies that this is done by adding up royalties for each individual patent. Moreover, the individual compensation is given as the ex-ante incremental value of the individual technology to the industry given all available technologies before the standard setting.

When it comes to interpretation of FRAND, most economists and legal experts agree that a *reasonable* royalty should be based on hypothetical arms-length negotiation at the time the standard is being set (e.g. Swanson and Baumol 2005; Geradin 2013; Lemley and Shapiro 2013; Carlton and Shampine 2013; Sidak 2013). This also follows from the patent law exemplified by Georgia-Pacific factors. For *non-discrimination*, a narrow definition requires the same royalty for all licensees, while a broader definition requires only similar users should pay similarly (Gilbert, 2011; Carlton and Shampine, 2013). Moreover, the principle should also extend to the owner herself (Swanson and Baumol, 2005). For *fairness*, there is hardly any paper discussing how to define it precisely in the context of FRAND.[8] As mentioned, the literature often use FRAND and RAND interchangeably.

So how are FRAND terms determined? Swanson and Baumol (2005) propose non-discriminatory compensation should be determined by *Efficient Component Pricing Rule* (ECPR) when the standard involves only one technology. It was developed as a pricing rule for service in public utility bottlenecks. In the current context, it requires a vertically integrated patent holder to set the royalty price equal to the price of the final good sold by the patent holder net of marginal cost of the patent holder. They argue that ECPR is reasonable when there is a substitutable technology or downstream entry barrier is low.[9]

However, ECPR relies on the fact that the patent owner is a vertically integrated firm, and that the standard is implemented by one patent. Layne-Farrar et al. (2007) and Schmalensee (2009) consider a standard consisting of two complementary components. Their extended ECPR-rule implies that the sum of the royalty rates of two components cannot exceed the incremental value of the standard. The sharing of royalty revenue is decided by having the SSO holding simultaneous auctions for each component. However, except for some special cases, there will be many equilibria, and it is not easy to determine which equilibrium one should select.

Efficiency based rules such as ECPR take market outcomes as benchmark, and does

[8] The problem of fair division has a long line of history. See e.g., Moulin (2004) and Hougaard (2009).

[9] In particular, when two technologies are perfect substitute, their ECPR-determined licensee fee implies zero compensation, consistent with our result.

not explicitly consider equity. Various cooperative game theory concepts, such as the Shapley value, (Layne-Farrar et al., 2007; Dehez and Poukens, 2013; Dewatripont and Legros, 2013; Pentheroudakis and Baron, 2017) captures the fairness notion, but may offer payment to viable technologies that are unlikely to be included in the final standard. Therefore, Sidak (2013) criticizes direct application of the Shapley value. For instance, technologies that are perfect substitutes should receive zero payment according to what would be a reasonable compensation. Indeed, in our model, a patent holder with zero incremental value to the standard does not receive compensation.

Regarding market outcome, Gilbert (2011) considers Nash bargaining solution for FRAND licensing terms. Lemley and Shapiro (2013) propose a market-based implementation of FRAND: only when there is disagreement on the licensing term, they are obligated to enter into binding final offer arbitration by experts. Layne-Farrar and Llobet (2014) argue that the incremental value approach (e.g. ECPR rule by Swanson and Baumol 2005) may fail to choose an efficient technology when the technology can be applied to multiple markets, and the SSO chooses standards based on maximizing profits of patent owners and downstream producers. Lerner and Tirole (2015) suggest that market outcome under price cap commitment is sufficient to restore ex-ante competition and efficiency, and that there is no need to impose FRAND commitment.

Our paper sheds light on the recent growing literature on litigation issues related to FRAND compensation (e.g.Ratliff and Rubinfeld 2013; Langus et al. 2013; Sidak 2015; Choi 2016). These papers study how the royalty is determined in the bargaining under the shadow of FRAND determination by court. Without a universally accepted definition of FRAND, both the patent holder and implementors can exploit legal uncertainty, leading to opportunistic behaviors. We suggest a precise definition of FRAND that services to resolve the dispute over different compensation rules, and thereby reduces legal uncertainty.

Finally we note that the suggested allocation method, based on firm-specific liability indices, is inspired by the approach of Hougaard and Moulin (2014). They consider the case where agents (firms) share the cost of access to an existing set of public goods (technologies), and agents preferences are given in the form of subsets of these public goods that provide them with service. In the present paper, we allow agents to have general utilities over subsets of the technologies. This makes a significant difference since, for each firm, it now becomes meaningful to allocate the worth of having access to all technologies among these individual technologies, given the cooperative game induced by the firms value function itself: this allocation we interpret as a natural representation of the firms liability for each of the individual technologies.

Content: The paper is organized as follows: Section 2 introduces the model. Section 3 and 4 present our proposed definition of a reasonable and fair compensation. Section 5 applies our notion of FRAND compensation to various scenarios in standard setting. Section 6 provides a short discussion of other potential applications. Section 7 closes with concluding remarks. All proofs will be in Appendix.

2 Model

We consider a group of firms (for instance a vertical cooperative structure, a standard setting organization, or a patent pool) for which the members in effect are locked-in, at least in the short run. The group shares access to a set of technologies (broadly interpreted as; patents, know-how, technology, resources) which they can use without rivalry: that is, the group shares a set of public goods from which all members can benefit both as a group, and as individual firms in different ways.

Formally, let $N = \{1, \ldots, n\}$ be a finite set of $n \geq 2$ firms. Each firm $i \in N$ is endowed with a technology r_i. Let $R = \{r_1, ..., r_n\}$ denote the profile of technologies. We may think of technology r_i as being owned, or controlled, by firm i. Therefore, some firms may have a double role as patent holder (licenser) and implementer (licensee), while other firms may be pure patent holders or, if their technology is non essential, pure implementers.

Let $v : 2^R \to \mathbb{R}$ be a function representing the value that the group for firms N obtain from having access to subsets of technologies $D \subseteq R$; for instance $v(R)$ represents the value of the group (e.g., a patent pool) from having access to all technologies (patents) R. We set $v(\phi) = 0$.[10]

Moreover, for a given firm $i \in N$, let $u_i : 2^R \to \mathbb{R}$ be a function representing the value firm i obtains from having access to subsets of technologies $D \subseteq R$ when all other firms in N have access to these technologies as well. [11] For instance, in a patent pool, $u_i(R)$ is the value of firm i from having access to all the technologies in the pool, R.

In our applications we sometimes explicitly assume that $v(D) = \sum_{i \in N} u_i(D)$, or that the value function v, and individual functions u_i, are *monotonic*, i.e., $v(D) \leq v(D')$ and $u_i(D) \leq u_i(D')$ for all $D \subseteq D'$. But none of these assumptions are needed for our general framework. They are only imposed when they simplify the analysis or illustration, and

[10] If the group is able to generate some value without any technology, we may have $v(\phi) > 0$. In this case, every formula remains unchanged except that total sharable surplus (royalty) is $v(R) - v(\phi)$ instead of $v(R)$.

[11] Lerner and Tirole (2015) consider a model of SSO where firm heterogeneity is represented by parametric distribution θ representing opportunity cost such that the value for firm $i \in N$ as $u_i(D) = u(D) - \theta$ for $D \subseteq R$ for some function u.

may be questionable in general (see e.g., Lerner and Tirole 2015). In practice, the presence of various types of externalities will often imply that $v(D) > \sum_{i \in N} u_i(D)$.

The problem: We ask how the firms in N should compensate each firm j for giving the group access to its technology r_j, and subsequently, how it should divide the cost of compensating firm j among members of the group in a *Fair, Reasonable and Non-Discriminatory* (FRAND) way based on the groups value function v as well as the profile of firm-specific value functions $u = (u_1, \ldots, u_n)$.

In the following we interpret "Reasonable" as referring to the *size* of the compensation to each technology owner, "Fair" as referring to the *allocation* of payments among the group of firms that covers this compensation, and "Non-Discriminatory" as referring to *anonymity* (or equal treatment) of firms in the group both when finding the size of their compensation and when royalty payments are determined. So unlike some authors (e.g., Carlton and Shampine 2013), we see an important difference between FRAND and RAND.

Since we shall base our definition of a reasonable compensation on the groups' value function v, this part will rely on *social* value, while our definition of fair royalty payments will refer to the firm-specific value functions u_i, and thereby rely on *individual* values. As such, our approach makes a clear distinction between using social and individual value information in the context of FRAND licensing terms: an issue which often seems mixed up in the literature (see e.g., Layne-Farrar and Llobet 2014).

3 Reasonable Compensation

We submit that a *reasonable* compensation to firm j is given by

$$M_j = v(R) - v(R \setminus \{r_j\}), \tag{1}$$

i.e., the incremental value of the group N from having access to technology $r_j \in R$. That is, the value M_j equals the upper bound of what the group is willing to compensate firm j for adding its technology, r_j, to the common pool. So if two technologies are perfect substitutes the incremental value to the group will be zero for both technologies and they will not be eligible for compensation. This seems to be in line with the Law and Economics literature that interprets the upper bound of a "reasonable" compensation as the incremental value over the next best alternative available in an ex-ante market (see e.g., Lemley and Shapiro 2013; Sidak 2013; Lerner et al. 2016). It is also in line with court rulings that considers the upper bound to be the result of a hypothetical negotiation before standard setting: in bargaining between two sellers with substitutable items, price is set competitively (e.g., *Microsoft v. Motorola*).[12]

It seems natural to assume that the total willingness to pay for all technologies does not exceed the groups value from having access to all the technologies, i.e., we assume that $\sum_{i \in N} M_i \leq v(R)$. Otherwise, for instance in case of *royalty stacking* where every patent holder expect to obtain the ex-ante incremental value of their technology, but the sum of these exceeds the market value of the end product, the compensation has to be downward adjusted in order for the standard to be economically viable.[13] Here we suggest to use a simple proportional down-scaling in line with our general fairness idea, i.e., as σM_j, for all j, where $\sigma = v(R)/\sum_{i \in N} M_i$.

When addressing issues of fair allocation it is conventional to apply the tools of cooperative game theory (see e.g., Moulin 2004; Hougaard 2009). This approach can also be applied to find reasonable compensations to technology owners as initially suggested in Layne-Farrar et al. (2007). In the context of our framework, their straightforward application consider the game (R, v) where R is the set of technologies and v is the group value function. Using the Shapley value with respect to (R, v) would allocate the total worth $v(R)$ among the individual technologies in R based on the weighted average of the groups incremental gains from adding the given technologies to any subset of R. This value can then be interpreted as the compensation that the respective technology owners should receive. However, this type of direct approach has been criticized in the literature (see. e.g., Sidak 2013) since some firms may be rewarded although their technology is worthless for the group as whole, for instance in case of substitutes (simply because the marginal value of adding these technologies to some subcoalition may be positive). Our approach using the incremental value (with potential downscaling) avoids this critique. Moreover, in the next section when considering a fair way to divide the cost of compensation, we shall use the Shapley value in a completely different way so this critique does not apply to that part of our analysis either.

[12] The ex-ante incremental approach may fail to achieve the first best outcome from the social planner perspective (Layne-Farrar and Llobet 2014) when technologies can be used in different industries. They show that firms strategically choose a less versatile technology to lessen product market competition.

[13] Shapiro (2001) argues that royalty stacking is a natural consequence of disperse ownership of technologies, similar to double marginalization. Siebrasse and Cotter (2016) and Pentheroudakis and Baron (2017) emphasize a FRAND royalty should minimize the risk of royalty stacking. Recent court rulings (for example, the case *Microsoft* v. *Motorla* in 2012) also suggest the ruling should take royalty stacking into account.

4 Fair Royalty Payment

The problem of fair division of a common resource has a long line of history (see e.g., Moulin 2004; Hougaard 2009). In our context, we ask how firms characterized by their individual value functions u_i should fairly compensate technology owner j for adding technology r_j to the common pool. Thus, in effect, we are asking how a group of agents should split the cost of sharing a set of public goods, which may contain redundancies (in the sense that the composition of the group, and the set of available technologies, may not be optimally chosen from the outset). The literature covering this particular situation is very sparse and the papers closest related to our context are Hougaard and Moulin (2014, 2017).

Fix the set of firms N and technologies R. A *royalty payment problem* is a pair (u, M) where u is the profile of firm specific value functions and $M = (M_1, \dots, M_n)$ is the profile of technology compensations derived from the groups' willingness to pay for each technology given the complement technologies are available. As argued in the previous section, without loss of generality, we assume $\sum_{i \in R} M_i \leq v(R)$.

An *payment rule* assigns to any problem (u, M) a vector of payments, $t(u, M) \in \mathbf{R}^n_+$. For every i, t_i is the total royalty that i must pay to compensate technology owners (including themselves). We assume payment rules are budget-balanced, i.e., $\sum_{i \in N} t_i = \sum_{j \in R} M_j$.

Since the size of the compensation is settled to be M_j for each technology $r_j \in R$, and this was determined in line with the general consensus about what a *reasonable* compensation should be, the challenge is now to define what we mean by a fair and non-discriminatory allocation rule which will distribute the payment of the compensation amongst the firms in N. In line with the traditional welfare theoretic approach we will capture this by defining a set of requirements (axioms), each representing some aspect of royalty payments build on FRAND terms.

Our first requirement is a classic independence property. We assume that any relevant payment rule is *Additive* in compensation, i.e., $t(u, M + M') = t(u, M) + t(u, M')$. The additivity assumption is standard fare in the literature on fair allocation and it implies that payment rules take the form,

$$t(u, M) = \sum_{j \in R} y(u, r_j) M_j, \tag{2}$$

where $y(u, r_j) \in \Delta(N)$ (with $\Delta(N)$ being the $N-$simplex) specifies how the compensation M_j for technology r_j is shared relatively amongst firms in N (Hougaard and Moulin, 2014). We will talk about $y(u, r_j)$ as a profile of firm-specific *liabilities* for compensation of technology $r_j \in R$: that is, the royalty payment of firm i, to technology owner j, is given by $y_i(u, r_j)M_j$. By focussing on additive payment rules we emphasize that fair liabilities (and thereby royalty payments) for a given technology r_j do not depend on the size of compensation M_j, or the size of any other technology compensation for that matter, but rather on the firm-specific value functions: that is, the way that the individual firms benefit from using the available technologies of the pool. This seems to play a crucial role for the incentive to innovate since it ensures that liabilities are correlated with individual firm value, given the market structure.

We will further assume that any relevant payment rule satisfies *Anonymity*, i.e., that payments are independent of the labeling of the firms. Indeed, this is a basic requirement of non-discrimination.

Moreover, we will require that the rule is *Consistent*[14] in the sense that removing a firm from the group after it has paid its royalty and reallocating the remaining compensation that has to be paid by the remaining firms does not lead to different royalty payments for these firms. Formally, considering additive payment rules, for any problem, and technology $r_j \in R$,

$$y_{-i}(u, r_j) = (1 - y_i(u, r_j)) \times y(u^{-i}, r_j)$$

where (u^{-i}, r_j) is the reduced problem where firm i is excluded from N and u^{-i} is the profile of the remaining firms value functions.

As shown in Hougaard and Moulin (2014), anonymity together with consistency (given additivity) implies that liabilities $y(u, r_j)$ are proportional to a given *liability index* $\ell(u_i, r_j)$ specific to each firm i, i.e.,

$$y_i(u, r_j) = \frac{\ell(u_i, r_j)}{\sum_{h \in N} \ell(u_h, r_j)} \quad \text{for all } i \in N \tag{3}$$

where $\ell(u_i, r_j) \geq 0$ is the liability index of firm i for technology r_j.

So combining with (2) we get that total royalty payments should take the form;

$$t_i(u, M) = \sum_{j \in R} \frac{\ell(u_i, r_j)}{\sum_{h \in N} \ell(u_h, r_j)} M_j, \quad \text{for all firms } i \in N \tag{4}$$

[14]Note that technically speaking consistency requires that we work with a variable populations framework which we avoid here for simplicity of notation since we do not aim at presenting a formal axiomatic characterization of our suggested indices.

As mentioned above the individual properties; additivity, anonymity and consistency are all well established and normatively compelling requirements from the theory of fair allocation (see e.g., Thomson 2012 for further justification), but also the consequence of applying them together, i.e., fairness in the form of proportionality to some individual characteristic, can be traced all the way back to Aristotle's writings on distributional justice.

Yet, it remains to argue for a desirable liability index $\ell(\cdot,\cdot)$. Noting that for each firm $i \in N$ the pair (R, u_i) constitutes a cooperative game (where the technologies can be construed as the "players") one obvious suggestion, in line with the conventional approach in the cost sharing literature, would be to use solution concepts from the theory of cooperative games as liability indices: for instance, the celebrated Shapley value,

$$\ell^S(u_i, r_j) = s_j(R, u_i) = \sum_{D \subseteq R \setminus \{r_j\}} \frac{|D|!(n - |D| - 1)!}{n!}(u_i(D \cup r_j) - u_i(D)), \tag{5}$$

for all $r_j \in R$. The normative foundation of the Shapley value is well known and there exists several axiomatic characterizations, see e.g., Shapley (1953); Peleg and Sudhölter (2007), which in principle, can be combined with the three requirements of additivity, anonymity and consistency in order to produce an axiomatic foundation of compensations in the form of (4) with the use of the Shapley liability index (5).

Example 1. Consider, as in Layne-Farrar et al. (2007), three technologies holders where technology 1 is essential and technologies 2 and 3 are imperfect substitutes. In particular, we have $v(\{r_1, r_2\}) = v(\{r_1, r_2, r_3\}) = 1 + \delta > 1 = v(\{r_1, r_3\})$ and $v(D) = 0$ otherwise. Computing the Shapley value of the game (N, v), Layne-Farrar et al. (2007) get compensations to firm 1, 2, and 3 respectively as $M_1^s = \frac{2}{3} + \frac{\delta}{2}$, $M_2^s = \frac{1}{6} + \frac{\delta}{2}$, and $M_3^s = \frac{1}{6}$.

Using our approach reasonable compensations should be determined by (1), i.e., as the marginal contributions of technologies 1, 2, and 3, respectively, to the group: $M_1 = 1 + \delta, M_2 = \delta$, and $M_3 = 0$; with gross compensation being $(1 + \delta)\sigma$, $\delta\sigma$, and 0 where $\sigma = (1 + \delta)/(1 + 2\delta)$. Clearly, this differs from the above Shapley compensations: $\sigma M_1 \geq M_1^s$ for all $\delta \geq 0$, while $\sigma M_2 \leq M_2^s$ for $\delta \in [0, 1]$; so our approach gives more compensation to firm 1 and less to firm 3, while for firm 2, it depends on the size of δ. The Shapley compensation gives a positive compensation to firm 3 (being 1/6), but this is unfortunate since it may lead to patent thicket as noted in Shapiro (2001). In contrast, our approach coincides the market/efficiency-based approach by Swanson and Baumol (2005) because competition between firms 2 and 3 will drive the compensation of firm 3 to zero.

Moreover, our approach also determine how this (reasonable) compensation is shared amongst the firms in the form of royalty payment. In particular, firm specific profits can be given by,[15]

$$\begin{aligned}
u_1\left(\{r_1,r_3\}\right) &= \frac{3}{4},\ u_2\left(\{r_1,r_3\}\right) = u_3\left(\{r_1,r_3\}\right) = \frac{1}{8} \\
u_1\left(D\right) &= \frac{3}{4}\left(1+\delta\right);u_2\left(D\right) = u_3\left(D\right) = \frac{1}{8}\left(1+\delta\right)\ \text{ for } D = R, \{r_1,r_2\} \\
u_i\left(D\right) &= 0 \text{ otherwise.}
\end{aligned}$$

The Shapley liability index (5) for firm 1, with respect to technology r_1 is

$$\begin{aligned}
& s_1(R,u_1) \\
=& \frac{1}{3}(u_1(R)-u_1(\{r_2,r_3\}))+\frac{1}{3}u_1(\{r_1\})+\frac{1}{6}(u_1(\{r_1,r_2\})-u_1(\{r_2\}))+\frac{1}{6}(u_1(\{r_1,r_3\})-u_1(\{r_3\})) \\
=& \frac{1}{8}(4+3\delta).
\end{aligned}$$

Since the sum of liabilities of all firms for r_1 is $\frac{1}{6}(4-3\delta)$ we get firm 1's proportional liability to be

$$y_1(u,r_1) = \frac{3}{4}.$$

Similarly, we can show that $y_1(u,r_2) = y_1(u,r_3) = \frac{3}{4}$. For firms 2 and 3, liabilities are also identical for all technologies and we get,

$$y_2 = y_3 = \frac{1}{8}.$$

Hence, total royalty paid by firm 1 to firm 2 is $\frac{3}{4}\sigma\delta$, and 0 to firm 3, while firm 1 receives $\frac{2}{8}\left(1+\delta\right)\sigma$ in total from firms 2 and 3. Similarly, firm 2 pays $\frac{1}{8}(1+\delta)\sigma$ to firm 1 and 0 to firm 3, while firm 2 receives $(\frac{3}{4}+\frac{1}{8})\delta\sigma$ in total from firms 1 and 3. Finally, firm 3 pays $\frac{1}{8}(1+\delta)\sigma$ to firm 1, and $\frac{1}{8}\delta\sigma$ to firm 2, while receiving no payment from the other firms. □

We emphasize that any compelling solution concept from cooperative game theory can potentially be applied as liability index.

Remark: In Hougaard and Moulin (2014), the agents (here firms) are characterized by sets of items (here technologies) which can provide them with service. That is, for any

[15] These profit functions can be rationalized using a standard Cournot setting, with one upstream, two downstream firms, and linear demand.

subset of the items, agents preferences are dichotomous (either satisfied or dissatisfied). In the present paper we extend to preferences modeled by any value function u_i. Using the Shapley value as liability index is not desirable in the context of Hougaard and Moulin's simple games due to the (implicit) normalization of these games. In our more general context of value functions u_i we avoid the problem connected with the normalization making the Shapley value a desirable candidate for a liability index.

5 Implementation

We have assumed every firm owns a technology so when the group is sharing the benefits from pooling these technologies all participating firms take part in dividing these benefits. However, in practice we may face situations where (i) some firms benefit from sharing the pool, but do not contribute with a technology (for instance, if their "technology" is non-essential making them implementers only), or (ii) some firms contribute more than one technology to the pool.

For case (i), we may need to distinguish between the set of firms $I \subseteq N$ that contributes with a technology, and hence has to be compensated, and those who do not $N \setminus I$. For instance, in some patent pools, firms within the pool does not compensate each other, but they will share their royalty revenue from firms outside the pool.

For case (ii), we can combine several technologies into one "technology package" so that each firm only has one "technology package".[16] This natural grouping of technology by ownership has at least four desirable features. First, this grouping is consistent with reasonable compensation. Consider a firm with two perfectly substitutable technologies. As both technologies jointly have a positive contribution to the standard, any reasonable compensation should be positive. Moreover, a market-based approach as in Swanson and Baumol (2005) would also require grouping of technologies by ownership as the firm with perfect substitute technologies would only need to sell one of these technologies. All the arguments above apply when a firm have imperfectly substitutable or even complementary technologies. Second, as the distribution of patent value is highly skewed in many industries (Schankerman, 1998), but companies may hold more than hundreds of patents related to the standard (Leonard and Lopez, 2014), finding Shapley liability index would

[16] Alternatively, we may consider a firm with multiple technology splitting up into individual firms with one technology. While this splitting is consistent with non-discrimination principle to require equal treatment regardless of the ownership, this may be less attractive under reasonableness consideration. Consider a firm with two perfectly substitutable technologies. As both technologies jointly have a positive contribution to the standard, reasonable compensation should be positive. However, splitting up technology under our approach would imply zero reasonable compensation.

be computationally heavy without grouping. For example, in Qualcomm case discussed in Example 4, almost all relevant patents are owned by three firms, the upstream firm (Qualcomm) and two other downstream firms (Huawei and ZTE). While one standard may involve more than thousands of patents, we only to consider three technology "package", which greatly simplifies computation. Third, this simplification is useful since most patents have low value, and even for technologies useful to a standard, it is sometimes very hard to measure its incremental value (Leonard and Lopez, 2014). Therefore, grouping technologies by ownership could by-pass the difficulties of measuring the incremental value of each technology. Forth, grouping technologies by ownership encourages firms spend money on complementary and value-enhancing innovation. This is consistent with private incentive of firms: maximization of value of their patent portfolio.

The calculation of our FRAND royalties requires the estimation of individual values of technology access u_i and group value v. Compared to approaches without individual values, our approach seems to require a lot of information. However, our approach needs no more information than what is required by the *Georgia-Pacific* factors which also requires individual values. Indeed, as shown in the next section, the calculation of individual values can be simplified with information of market structure and market characteristics.

6 Application

We will now illustrate how firm-specific values can be determined using information of market competition. We consider two different market structures: (1) horizontal – all firms are downstream producers; and (2) vertical – some firms are upstream producers, and some firms are downstream producers.[17] Following the literature in industrial organization, we focus on cost reducing innovations, which is isomorphic to value enhancing innovation (Tirole, 1988).

In the following, when we determine liabilities of individual firms, we mean liabilities in the form of (3) using the Shapley liability index (5), unless explicitly stated otherwise.

6.1 Horizontal Market

Following the innovation literature initiated by Arrow (1962), we consider process innovations in a homogeneous good market. A prominent example is portable storage devices

[17] We focus on Cournot competition for the downstream market, noting that Bertrand competition would deliver similar results.

such as memory card/sticks where the homogeneous good assumption is a good approximation.

6.1.1 Single Product Market

We consider a single product market where firms are symmetric in the sense that they have identical cost functions except for fixed cost, and face the same market demand. This implies that in every symmetric equilibrium, for every firm $i \in N$, we have $u_i(D) = \bar{u}(D) - \theta_i$ for all $D \subseteq R$ where θ_i is the fixed cost of firm i and $\bar{u}(D)$ is the equilibrium profit when all firms have access to D.[18] The compensation for individual technologies may differ, but the liabilities of each firm, for each technology, are identical across firms. We record this observation in Proposition 1, below.

Proposition 1 *Consider a horizontal cooperative agreement between n symmetric firms. Under FRAND compensation, firm i's liability for technology $r_j \in R$ is,*

$$y_i\left(u, r_j\right) = \frac{1}{n}.$$

To illustrate the result, we consider a Cournot model with linear demand, zero fixed cost and constant marginal cost. When firms have access to the set of technologies $D \subseteq R$, they have a constant marginal cost c_D.

Example 2. The inverse market demand is given by $P = a - Q$ where $Q = \sum_{i \in N} q_i$ is the aggregate production and q_i is production by firm $i \in N$. The profit of firm i with access to technology D is $u_i(D) = (p - c_D)q_i$. Standard calculation shows that equilibrium production and profit of firm i are $q_i(D) = \frac{a - c_D}{n+1}$ and $\pi_i(D) = q_i^2(D)$. Therefore, when each firm has access to R, firm i pays total royalty $t_i = \sum_{r_j \in R} y_i(u, r_j) M_j$.[19] Thus firm i's per unit royalty for technology j becomes

$$\tau_i(j) = \frac{y_i(u, r_j) M_j}{q_i(R)} = \frac{M_j}{n q_i(R)}.$$

It is useful to compare our model to some existing rules. Under the symmetric case, our approach should be similar to some of the rules adopted in the literature because non-discrimination implies fairness under a symmetric setup. Sidak (2013) mention two

[18]This is equivalent to Lerner and Tirole (2015) where they consider firm has different opportunity cost for using technology.

[19]Note that the compensation to technology r_j would be σM_j if $\sum_{j \in R} M_j > v(R)$.

methodologies for calculating FRAND royalty: (i) *top down* and (ii) *proportional contribution*. We will show that our rule leads the same outcome as the top down approach and similar outcomes for the proportion contribution approach.
(i) The top-down approach considers per unit FRAND royalty as:

$$\text{price of smallest salable component} \times \text{Average profit margin} \times \frac{\text{Contribution of Patent}}{\text{Value of standard}}.$$

Assuming that the product itself is already the smallest salable component, the standard involves all the technologies, and the value of standard is $v(R)$,[20] we have

$$\text{per unit royalty} = (p - c_R) \times \frac{M_j}{v(R)} = (p - c_R) \times \frac{M_j}{\sum_{i \in N}(p - c_R)q_i(R)} = \frac{M_j}{nq_i(R)} = \tau_i(j).$$

Thus, our approach delivers exactly the same result.
(ii) proportional contribution considers per unit FRAND royalty as:

$$\text{price of final product} \times \frac{\text{Contribution of Standard}}{\text{Value of Product}} \times \frac{\text{Contribution of Patent}}{\text{Value of standard}}$$

Since the standard is fully utilized by all firms, we assume that "contribution of standard to value of product" is 1. Then we have

$$p \times \frac{M_j}{v(R)} = p \times \frac{M_j}{(p - c_R)\sum_{i \in N} q_i(R)} = \frac{p}{p - c_R} \times \frac{M_j}{nq_i(R)} = \frac{p}{p - c_R} \times \tau_i(j).$$

That is, our approach delivers similar results as the proportional contributions rule adjusted by the relative markup. □

Proposition 1 shows that when firms are symmetric, the resulting FRAND liabilities are the same. It is natural to expect that when firms are ex-ante asymmetric, it may lead to differences in firm liabilities. To illustrate this, we consider the linear Cournot case as in Example 2, but the marginal cost of production for every firm $i \in N$ with technology $D \subseteq R$ is $c_i(D)$. Denote $q_i(D)$ be the equilibrium quantity of firm i when all firms have access to D. Under this case, it may be convenient to allow $u_i(\emptyset)$ can be greater than zero for some firm i to reflect ex-ante asymmetry between firms. In this case, we may have $v(\emptyset) > 0$ if we assume $v(D) = \sum_{i \in N} u_i(D)$.

[20] Strictly speaking, the value of standard should be $v(R) - v(\emptyset)$. We have normalized $v(\emptyset) = 0$, which is implied by the fact that the market would not exist without any of technology $r \in R$. In current Cournot case, the condition is equivalent to $c_\emptyset \geq a$. Hence, if $v(\emptyset) > 0$, our FRAND royalty is different from top down approach.

Example 3. Focusing on the two-firm case. Straightforward computations show that under FRAND compensation firm 1's liability for technology $r_1 \in R$, is

$$y_1(u, r_1) = \left(1 + \frac{q_2^2(R) - q_2^2(\{r_2\}) + q_2^2(\{r_1\}) - q_2^2(\emptyset)}{q_1^2(R) - q_1^2(\{r_2\}) + q_1^2(\{r_1\}) - q_1^2(\emptyset)}\right)^{-1}.$$

Hence, firm 1's per unit FRAND royalty for technology r_1 is

$$\frac{y_1(u, r_1)M_1}{q_1(R)} = \frac{M_1}{q_1(R)\left(1 + \frac{q_2^2(R) - q_2^2(\{r_2\}) + q_2^2(\{r_1\}) - q_2^2(\emptyset)}{q_1^2(R) - q_1^2(\{r_2\}) + q_1^2(\{r_1\}) - q_1^2(\emptyset)}\right)}.$$

For comparison, the top down approach gives the per unit royalty as

$$(p - c_1(R))\frac{M_1}{v(R) - v(\emptyset)} = \frac{M_1}{q_1(R)\left(1 + \frac{q_2^2(R) - q_2^2(\emptyset) - q_1^2(\emptyset)}{q_1^2(R)}\right)}.$$

So according to the top down approach, royalty payment depends on the ratio of total profit. The proportional contribution approach gives the per unit royalty as

$$p \times \frac{M_1}{v(R) - v(\emptyset)} = \frac{p}{p - c_1(R)} \times \frac{M_1}{q_1(R)\left(1 + \frac{q_2^2(R) - q_2^2(\emptyset) - q_1^2(\emptyset)}{q_1^2(R)}\right)}.$$

Both the top down and proportional contribution approaches are different from our approach as they only rely on the case where firms have access to all technologies, but not any other possible cases where only subsets of technologies are available. Moreover, our approach focusses on cost reducing technologies and thereby on marginal changes of the profit due to technology adaption. Hence, when all technologies are truly essential (i.e., all have to be present to produce value: $q_i(\emptyset) = q_i(\{r_1\}) = q_i(\{r_2\}) = 0$ for all $i \in N$), our approach coincides with the top-down rule. □

The following proposition further illustrate our approach in the standard case that marginal cost of production is $c_i(D) = c_i(\emptyset) - \theta_i \epsilon_D$, where $c_i(\emptyset)$ is the marginal cost of firm i with existing technology (not using any technology in R) and ϵ_D is the cost saving brought by technology $D \subseteq R$. For simplicity, suppose there are two firms and technologies are perfectly compatible ($\epsilon_R = \epsilon_{r_1} + \epsilon_{r_2}$). (for the general case, see Appendix B).

Proposition 2 *Consider a horizontal cooperative agreement between 2 firms engaging in*

Cournot competition, producing homogeneous products. Suppose technologies are perfectly compatible ($\epsilon_R = \epsilon_{r_1} + \epsilon_{r_2}$)*. Under FRAND compensation, (a) the liability for* $r_j \in \{r_1, r_2\}$ *by firm* $i \in \{1, 2\}$ *is*

$$y_i(u, r_j) = \frac{1}{1 + \frac{(2\theta_k - \theta_i)\sum_{D\subseteq R} q_k(D)}{(2\theta_i - \theta_k)\sum_{D\subseteq R} q_i(D)}} \text{ where } k = \{1,2\}\backslash\{i\}.$$

(b) When both firms have the same efficiency parameter ($\theta_1 = \theta_2$)*, we have*

$$y_i(u, r_j) = \frac{1}{1 + \frac{\sum_{D\subseteq R} q_k(D)}{\sum_{D\subseteq R} q_i(D)}} \text{ where } k = \{1,2\}\backslash\{i\}.$$

(b) When both firms have same marginal cost under the same access to technologies ($c_1(D) = c_2(D)$ *for all* $D \subseteq R$)*, we have*

$$y_i(u, r_j) = \frac{1}{2}.$$

As such, payment depends on the efficiency parameters (θ_i): the more efficient firm of the two will pay more in royalty than the less efficient firm, simply because access to the cost reducing technology is more valuable to the more efficient firm.

6.1.2 Multiple Product Markets

Following Schmalensee (2009), we consider competing firms producing heterogeneous products. The inverse demand function by firm i is $p_i = \alpha_i - \beta_i q_i - \gamma \sum_{j\in N\backslash\{i\}} q_j$.[21] Continue the assumption from above that marginal cost of production is $c_i(D) = c_i(\emptyset) - \theta_i \epsilon_D$. For exposition, we assume the market consists of two firms.

Proposition 3 *Consider a horizontal cooperative agreement between* 2 *firms engaging in Cournot competition, producing heterogeneous products. Suppose technologies are perfectly compatible* ($\epsilon_R = \epsilon_{r_1} + \epsilon_{r_2}$)*. Under FRAND compensation, (a) the liability for* $r_j \in \{r_1, r_2\}$

[21] Singh and Vives (1984) show that for the case of two firms that the demand function follows from the representative consumers that maximizes $U(q_1, q_2) - \sum_{i=1}^{2} p_i q_i$ where $U(q_1, q_2) = \alpha_1 q_1 + \alpha_2 q_2 - (\beta_1 q_1^2 + 2\gamma q_1 q_2 + \beta_2 q_2^2)/2$ where α_i and β_i are positive for $i = 1, 2$, and $\beta_1\beta_2 - \gamma^2 > 0$, and $\alpha_i\beta_j - \alpha_j\gamma > 0$ for $i \neq j$. Similar derivation can be applied to general cases of multiple firms (see e.g. Vives 1999; Häckner 2000).

by firm $i \in \{1,2\}$ is

$$y_i(u, r_j) = \frac{1}{1 + \frac{(\theta_k(2-\beta_i^2)-\gamma\theta_i)\sum_{D\subseteq R} q_k(D)}{(\theta_i(2-\beta_k^2)-\gamma\theta_k)\sum_{D\subseteq R} q_i(D)}} \text{ where } k = \{1,2\}\backslash\{i\}.$$

(b) In particular, (i) when both firms have the same productive efficiency ($\theta_1 = \theta_2$), we have

$$y_i(u, r_j) = \frac{1}{1 + \frac{(2-\beta_i^2-\gamma)\sum_{D\subseteq R} q_k(D)}{(2-\beta_k^2-\gamma)\sum_{D\subseteq R} q_i(D)}} \text{ where } k = \{1,2\}\backslash\{i\},$$

(ii) when both firms face symmetric markets ($\beta_1 = \beta_2 = \beta$), we have

$$y_i(u, r_j) = \frac{1}{1 + \frac{(\theta_k(2-\beta^2)-\gamma\theta_i)\sum_{D\subseteq R} q_k(D)}{(\theta_i(2-\beta^2)-\gamma\theta_k)\sum_{D\subseteq R} q_i(D)}} \text{ where } k = \{1,2\}\backslash\{i\}, \text{ and}$$

(iii) when firms are completely symmetric ($\theta_1 = \theta_2$ and $\beta_1 = \beta_2 = \beta$), we have

$$y_i\left(u, r_j\right) = \frac{1}{2}.$$

Part (b-iii) naturally follows from Proposition 1: if firms are completely symmetric, their liabilities are equal. Part (b-ii) is similar to Example 3: when markets are symmetric, the share depends on relative productive efficiencies explicitly. Note that when the market linkage γ is low, the ratio mainly depends on the relative efficiency θ_i/θ_j. Part (b-i) shows that when firms face different markets with the same productive efficiencies, our FRAND royalties would be different from the Top-Down approach and the Proportional approach. Part (a) shows that the liability ratio depends on both productive efficiencies and market asymmetries jointly.

6.2 Vertical Market

We now consider the case where upstream firms produce intermediate goods or provide resources to downstream firms under a vertical cooperative agreement, see e.g., Kim (2004); Dewatripont and Legros (2013).

6.2.1 Single Product Market

Suppose there are m upstream firms and l downstream firms. Let M and L be the sets of upstream firms and domstream firms respectively. Each downstream firm produce one unit of the final product using one unit of intermediate input from each upstream firm. An upstream firm i charges d_i for intermediary inputs that are necessary for downstream production. When firms have access to the set of technologies $D \subseteq R$, they have a constant marginal cost c_D. The profit of downstream firms $i \in L$ with access to technologies D are $\pi_i = (\alpha - \beta Q - \sum_{k \in M} d_k - c_D)q_i$ and that for upstream firms $k \in M$ are $\pi_k = d_k Q$ where $Q = \sum_{i \in L} q_i$.

Consider a two-stage game where all upstream firms first engage in Bertrand competition, and then subsequently all downstream firms engage in Cournot competition.

Proposition 4 *The liability for technology $r_j \in R$ by an upstream firm $i \in M$ is*

$$y_i(u, r_j) = \frac{l+1}{m(l+1)+1},$$

and the liability for downstream firm $k \in L$ is

$$y_k(u, r_j) = \frac{1}{l(m(l+1)+1)}.$$

Note that the liabilities depend on the market structure, but not on the market characteristics given by parameters α and β. As the number of upstream firms increases, liabilities for all firms reduce. On the other hand, as the number of downstream firms increases, the liabilities for upstream firms increase, but those for downstream firms decrease.

Example 5: An interesting example of a vertical cooperative agreement is reverse licensing imposed by Qualcomm (Ko and Zhang, 2016). Qualcomm is the world's largest smartphone chipmaker. Owning the key technology, Qualcomm is a near monopoly in the Chinese smartphone chip market.[22] For smartphone market major producers, there are two firms (Huawei and ZTE) owning the significantly more patents than other firms (e.g. OPPO and Xiaomi).[23] Qualcomm adopted the practice of *reverse licensing* without offsetting payment: (1) when Huawei and ZTE purchase chips and patents from Qualcomm, they have to surrender their own patents to Qualcomm for free, and (2) when Xiaomi and OPPO purchase the chips from Qualcomm, they get not only patents from Qualcomm,

[22] 100% market share in the market for licensing of each relevant wireless communications standard essential patents ("SEPs") and above 50% market share in CDMA, WCDMA and LTE baseband chip markets.

[23] As of 2014, ZTE (Zhongxing Telecommunication Electronic) and Huawei have roughly 30,000 and 52,000 patents while OPPO and Xiaomi have only 103 and 10 patents.

but also patents from Huawei and ZTE, without paying to them. Such a practice clearly hinders the incentive to innovate not only for Huawei and ZTE, as they gain nothing from their research, but also for Xiaomi and OPPO, as they free ride.

In November 2013, China's National Development and Reform Commission ("NDRC"), responsible for price-related violations of China's Anti-Monopoly Law, began investigating whether Qualcomm abused its dominant market position.[24] On March 2, 2015, NDRC published its decision regarding the anticompetitive conducts and ordered Qualcomm to cease the anti-competitive conducts and pay a fine of RMB 6.088 billion (approx. US$975 million). Moreover, Qualcomm could only charge fair and reasonable royalty to downstream firms in the future. Qualcomm announced that it would not contest the NDRC decision and agreed to change certain of its patent licensing and baseband chip sales practices in China.

We consider firm 1 (Qualcomm) as the upstream firm with technology r_1, and firms $2, ..., n$ as downstream firms. Downstream firms are competing in a Cournot market. Firm 2 (ZTE) and firm 3 (Huawei) have important technologies (patents) r_2 and r_3. Firms 4,..,n have no essential technologies to provide for the group.

Let $R = \{r_1, r_2, r_3\}$ be the set of relevant technologies. Since r_1 (technology and intermediate inputs by Qualcomm) is crucial for the entire construction of the agreement, for any $i \in N$, $u_i(D) = 0$ if $r_1 \notin D$. Qualcomm is a de facto monopoly in the market for smartphone chips so downstream smartphone producers have no outside option besides cooperating with Qualcomm. Therefore downstream firms have no potential profit without Qualcomm. Assume that $v(D) = \sum_{i \in N} u_i(D)$, for any $D \subseteq R$, is the total industry profit.

Finding a fair way to allocate the compensations among the members in N we apply the sharing rules (3) with the Shapley liability index (5). Thus, for each firm $i \in N$ we find the liability of each technology as the Shapley value of the game $(\{r_1, r_2, r_3\}, u_i)$.

Letting $s_j(R, u_i)$ be the Shapley liability index of technology j for firm i we get in the

[24]China is not the only country investigating Qualcomm's anticompetitive conducts. Before reaching an agreement in 2008, Nokia had complaint Qualcomm for charging expired patent and high royalty rates. In 2009, South Korea fined Qualcomm Won 260 billion (USD 207 million), for abusing market dominance positions. More recently, in 2015, EU started an investigation on predatory pricing, i.e. whether Qualcomm is driving competitors out of the market.

Qualcomm case that

$$
\begin{aligned}
s_1(R,u_i) &= \frac{1}{3}\left[u_i(\{r_1\}) + u_i(R)\right] + \frac{1}{6}\left[u_i(\{r_1,r_2\}) + u_i(\{r_1,r_3\})\right] \\
s_2(R,u_i) &= \frac{1}{3}\left[u_i(R) - u_i(\{r_1,r_3\})\right] + \frac{1}{6}\left[u_i(\{r_1,r_2\}) - u_i(\{r_1\})\right] \\
s_3(R,u_i) &= \frac{1}{3}\left[u_i(R) - u_i(\{r_1,r_2\})\right] + \frac{1}{6}\left[u_i(\{r_1,r_3\}) - u_i(\{r_1\})\right]
\end{aligned}
$$

since $u_i(D) = 0$ if $r_1 \notin D$. By Proposition 4, we know that liability for technology $r_j \in R$ by firm 1 (Qualcomm) is $y_1(u, r_j) = \frac{n}{n+1}$, and that by firms $i = 2, ..., n$, is $y_i(u, r_j) = \frac{1}{(n+1)(n-1)}$.

When technologies 2 and 3 are complementary, using the Shapley liability index is compelling since no technology subsidizes other technologies in the usual sense of the core. When technologies owned by firms 2 and 3 are perfect substitutes for each firm in the agreement, the core always assigns liability zero to the SEPs of firm 2 and 3, because $u_i(\{r_j\}) = u_i(R) - u_i(\{r_1, r_k\}) = 0$ for $j, k = 2, 3$ and $j \neq k$. However, the Shapley value may still give positive shares to the SEPs of firm 2 and 3, simply because their marginal contribution to r_1 may be positive. Since a reasonable compensation M_j is zero for perfect substitutes (and small if substitutes of some degree) the size of the liabilities plays a highly limited role in this case as the associated royalty payment will be negligible anyway. □

6.2.2 Multiple Product Market

For simplicity, consider only one upstream firm and $n-1$ downstream firms. Let the upstream firm to be firm 1. Under quadratic utility of the representative consumer, the demand function for firm $i = 2, \ldots, n$ is $p_i = \alpha - \beta q_i - \gamma \sum_{j \neq i,1} q_j$. When firms have access to the set of technologies $D \subseteq R$, they have a constant marginal cost c_D. The profit of the upstream firm $\pi_1 = dQ = d \sum_{j \in N \setminus \{1\}} q_j$ and the profit of a downstream firm $i \in N \setminus \{1\}$ is $\pi_i = (p_i - c_D - d) q_i = (\alpha - \beta q_i - \gamma \sum_{j \neq 1,i} q_j - c_D - d) q_i$. Consider a two-stage game where the upstream firm first decides the prices of intermediate inputs, and then all downstream firms engage in a heterogeneous Cournot competition.

Proposition 5 *Suppose the upstream firm decides the prices of intermediate inputs and downstream firms engage in a heterogeneous Cournot competition. The liability for technology $r_j \in R$ for the upstream firm is*

$$y_1(u, r_j) = \frac{2\beta + n\gamma}{3\beta + n\gamma},$$

and the liability of downstream firms $i = 2, ..., N$ are

$$y_i(u, r_j) = \frac{\beta}{(n-1)(3\beta + n\gamma)}.$$

Note that the level of substitutability of products of different firms, γ, enters the liability. We can check that $\frac{dy_1(u,r_j)}{d\gamma} > 0$, indicating that the upstream firm will pay more royalty as the downstream firms become more competitive; and $\frac{dy_i(u,r_j)}{d\gamma} < 0$ indicating that downstream firms pay less royalty as competition increases.

In line with the result from the single product market case, as the number of downstream firms increases, the liability of the upstream firm increases while the liabilities for all downstream firms decrease.

As markets become more elastic the same percentage of cost saving will lead to smaller improvement in the profit and thereby smaller liability for the upstream firm (i.e., $\frac{dy_1}{d\beta} < 0$).

7 Discussion

Our approach extends well beyond the application of FRAND compensation in standard setting. Below we sketch a few obvious areas for further application.

Application 1. Patent Pool. Firms with complementary patents often pool their patent together to save time to negotiate multilateral cross-licensing among patent holders (Shapiro, 2001). Lerner and Tirole (2004) shows that sharing ratio of royalty of patent members is important for the formation of a patent pool when patents are asymmetric. Layne-Farrar and Lerner (2011) empirically identify factors that affect the decision to join a patent pool. They show that fairness is important: (1) royalty-free rules will attract the lowest participation, (2) numerical proportional rule will be less attractive than value-based rules, and (3) firms with similar patent offerings are likely to form a patent pool. The fair sharing rule should take market structure into account as Kim (2004) and Lerner and Tirole (2004) show that outcome of patent pool depend on the vertical structures.[25]

Application 2. Research Joint Venture (RJV) After the National Cooperative Research Act of 1984 in US, research joint ventures have become common in industries that requires substantial investment in research and development. The key difference

[25]The interaction between SSO and patent pool can be complicated (e.g. Llanes and Poblete 2014). In particular, Miao (2016) shows that it is optimal for a patent pool to adopt a "reverse-non-discriminatory" licensing policy that pool members pay more than non-pool members.

between an RJV and an SSO is that members in an RJV agree what should be the appropriate allocation of benefits and costs when the RJV forms (Baron and Schmidt 2016). Katz and Shapiro (1986) show that the choice of cost sharing is important for an RJV: it has to be carefully selected for efficient research investment and formation of an RJV. In particular, for a vertical RJV, Banerjee and Lin (2001) studies how two different sharing rules changes the optimal size.

Application 3. Platform. A physical market (e.g. carnival or flea market) or an internet marketplace (e.g. Amazon) is providing a trading platform for buyers and sellers. Good (rich) buyers and good (reputable) sellers brings value to the marketplace while others are not bringing that much value. There is a large literature studying the positive outcome of platform (for example, Rochet and Tirole 2003; Armstrong 2006). For example, Rochet and Tirole (2003) consider the participation fees of the platforms run by either profit-maximizing firms or non-profit associations. While there are optimal pricing decision based on social welfare, there is no discussion of fair compensation from a normative approach. An additional access by an extra agent to the platform usually brings extra net benefit with minimal cost. The traditional cost-plus approach (Laffont and Tirole, 1993) as a fair pricing scheme is not applicable. Then one natural question is that what is the fair participation fee to the marketplace given there are complex externalities in play? Especially when the marketplace is organized by government, fairness to all participants is an important concern.

8 Concluding Remarks

To sum up our main contribution:

We provide a definition of FRAND that makes a clear distinction between Fair, Reasonable and Non-Discriminatory royalty payment.

- Our approach to fair royalty payment has an axiomatic foundation with normatively compelling properties widely accepted in the literature on fair allocation (Hougaard and Moulin, 2014).
- Our approach to reasonable compensation satisfies 'no contribution, no pay', so inferior substitute technologies has no value to the group and therefore are not eligible for payment (Sidak, 2013). This is also in line with the market-based idea of Swanson and Baumol (2005).

- Our approach takes the market structure into account via firm-specific value functions. This ensures that royalty payment is in line with the market value of individual firms for having access to the technology pool, which in turn, ensures the incentive to innovate (Siebrasse and Cotter, 2016).
- Our approach accounts for royalty stacking as well as patent hold-up, and thereby preserve the economic viability of standard (Pentheroudakis and Baron, 2017).
- Our approach delivers clearly specified royalty payments including what the patent owners should pay to themselves (a question posed by Swanson and Baumol 2005).
- Our approach clearly distinguishes between social and individual firm values (an issue that seems ambiguous in literature, Layne-Farrar and Llobet 2014).
- Our approach is in line conventional royalty rules like the Top-down, and the Proportional-contribution rule in the simple case of completely symmetric firms (here fairness coincides with non-discrimination). In the more complicated case of asymmetric firms our royalty payment depend explicitly on market conditions: our approach coincides with the Top-down rule only in case all technologies are truly essential. This reflects the flexibility in the FRAND terms: no obligation to ensure that every licensee receiving identical terms (Epstein et al., 2012).

References

Armstrong, Mark, “Competition in two-sided markets,” *The RAND Journal of Economics*, 2006, *37* (3), 668–691.

Arrow, Kenneth, “Economic Welfare and the Allocation of Resources for Invention,” in “The rate and direction of inventive activity: Economic and social factors,” Princeton University Press, 1962, pp. 609–626.

Banerjee, Samiran and Ping Lin, “Vertical Research Joint Ventures,” *International Journal of Industrial Organization*, 2001, *19* (1), 285–302.

Baron, Justus and Julia Schmidt, “Technological Standardization, Endogenous Productivity and Transitory Dynamics,” 2016. Working Paper.

Brooks, Roger G and Damien Geradin, “Interpreting and Enforcing the Voluntary FRAND Commitment,” *International Journal of IT Standards and Standardization Research (IJITSR)*, 2011, *9* (1), 1–23.

Carlton, Dennis W and Allan L Shampine, “An Economic Interpretation of FRAND,” *Journal of Competition Law and Economics*, 2013, *9* (3), 531–552.

Choi, Jay Pil, “FRAND Royalties and Injunctions for Standard Essential Patents,” *Global Economic Review*, 2016, *45* (3), 233–250.

Church, Jeffrey and Neil Gandal, “Network effects, software provision, and standardization,” *The journal of industrial economics*, 1992, *40* (1), 85–103.

Dehez, Pierre and Sophie Poukens, “The Shapley Value as a Guide to FRAND Licensing Agreements,” *Review of Law and Economics*, 2013.

Dewatripont, Mathias and Patrick Legros, “Essential Patents, FRAND Royalties and Technological Standards,” *Journal of Industrial Economics*, 2013, *61* (4), 913–937.

Epstein, Richard A, F Scott Kieff, and Daniel F Spulber, “The FTC, IP, and SSOs: Government Hold-Up Replacing Private Coordination,” *Journal of Competition Law and Economics*, 2012, *8* (1), 1–46.

Geradin, Damien, “The Meaning of Fair and Reasonable in the Context of Third-Party Determination of Frand Terms,” *George Mason Law Review*, 2013, *21*, 919.

_ , “FRAND Arbitration: The Determination of Fair, Reasonable and Non-Discriminatory Rates for SEPs by Arbitral Tribunals,” *Forthcoming, Antitrust Chronicle (Fall 2016)*, 2016.

Gilbert, Richard J, “Deal or No Deal? Licensing Negotiations in Standard-Setting Organizations,” *Antitrust Law Journal*, 2011, *77* (3), 855–888.

Häckner, Jonas, “A note on Price and Quantity Competition in Differentiated Oligopolies,” *Journal of Economic Theory*, 2000, *93* (2), 233–239.

Hougaard, Jens, *An Introduction to Allocation Rules*, Springer Science & Business Media, 2009.

Hougaard, Jens Leth and Hervé Moulin, “Sharing the Cost of Redundant Items,” *Games and Economic Behavior*, 2014, *87*, 339–352.

_ **and** _ , “Sharing the Cost of Risky Projects,” *Economic Theory*, 2017.

Katz, Michael L, “An Analysis of Cooperative Research and Development,” *The RAND Journal of Economics*, 1986, pp. 527–543.

_ **and Carl Shapiro**, “How to License Intangible Property,” *Quarterly Journal of Economics*, 1986, pp. 567–589.

Kim, Sung-Hwan, “Vertical Structure and Patent Pools,” *Review of Industrial Organization*, 2004, *25* (3), 231–250.

Ko, Chiu Yu and Xuyao Zhang, “Reverse Licensing,” 2016. Working paper.

Laffont, Jean-Jacques and Jean Tirole, *A Theory of Incentives in Procurement and Regulation*, MIT press, 1993.

Langus, Gregor, Vilen Lipatov, and Damien Neven, “Standard-Essential Patents: Who Is Really Holding Up (and When)?,” *Journal of Competition Law and Economics*, 2013, *9* (2), 253–284.

Layne-Farrar, Anne, A Jorge Padilla, and Richard Schmalensee, “Pricing Patents for Licensing in Standard-setting Organizations: Making Sense of FRAND Commitments,” *Antitrust Law Journal*, 2007, *74* (3), 671–706.

_ **and Gerard Llobet**, "Moving beyond Simple Examples: Assessing the Incremental Value Rule within Standards," *International Journal of Industrial Organization*, 2014, *36*, 57–69.

_ **and Josh Lerner**, "To Join or not to Join: Examining Patent Pool Participation and Rent Sharing Rules," *International Journal of Industrial Organization*, 2011, *29* (2), 294–303.

Lemley, Mark A and Carl Shapiro, "A Simple Approach to Setting Reasonable Royalties for Standard-essential Patents," *Berkeley Technology Law Journal*, 2013, *28*, 1135–1166.

Leonard, Gregory K. and Mario A. Lopez, "Determining RAND Royalty Rates for Standard-Essential Patents," *Antitrust*, 2014, *29* (1), 87–94.

Lerner, Josh and Jean Tirole, "Efficient Patent Pools," *American Economic Review*, 2004, *94* (3), 691–711.

_ **and** _ , "A Better Route to Tech Standards," *Science*, 2014, *343* (6174), 972–973.

_ **and** _ , "Standard-Essential Patents," *Journal of Political Economy*, 2015, *123* (3), 547–586.

_ **, Haris Tabakovic, and Jean Tirole**, "Patent Disclosures and Standard-Setting," Technical Report, National Bureau of Economic Research 2016.

Llanes, Gastón and Joaquín Poblete, "Ex Ante Agreements in Standard Setting and Patent-Pool Formation," *Journal of Economics and Management Strategy*, 2014, *23* (1), 50–67.

Ménière, Yann et al., "Fair, Reasonable and Non-discriminatory (FRAND) Licensing Terms. Research Analysis of a Controversial Concept," Scientific and Technical Research Reports, Join Research Center, European Commission 06 2015.

Miao, Chun-Hui, "Licensing a Technology Standard," *International Journal of Industrial Organization*, 2016, *47*, 33–61.

Moulin, Hervé, *Fair Division and Collective Welfare*, MIT press, 2004.

Peleg, Bezalel and Peter Sudhölter, *Introduction to the Theory of Cooperative Games*, Vol. 34, Springer Science & Business Media, 2007.

Pentheroudakis, Chryssoula and Justus Baron, "Licensing Terms of Standard Essential Patents: A Comprehensive Analysis of Cases," Scientific and Technical Research Reports, Join Research Center, European Commission 01 2017.

Ratliff, James and Daniel L Rubinfeld, "The Use and Threat of Injunctions in the RAND Context," *Journal of Competition Law and Economics*, 2013, pp. 1–22.

Rochet, Jean-Charles and Jean Tirole, "Platform competition in two-sided markets," *Journal of the European Economic Association*, 2003, *1* (4), 990–1029.

Schankerman, Mark, "How valuable is patent protection? Estimates by technology field," *RAND Journal of Economics*, 1998, pp. 77–107.

Schmalensee, Richard, "Standard Setting, Innovation Specialist and Competition Policy," *Journal of Industrial Economics*, 2009, *57* (3), 526–552.

Shapiro, Carl, "Navigating the Patent Thicket: Cross Licenses, Patent Pools, and Standard Setting," in "Innovation Policy and the Economy, Volume 1," MIT press, 2001, pp. 119–150.

Shapley, L. S., "A Value for n-person Games," in Harold W. Kuhn and Albert W. Tucker, eds., *Contributions to the Theory of Games (AM-28), Volume II*, Princeton University Press, 1953, pp. 307–318.

Sidak, J Gregory, "The Meaning of FRAND, Part I: Royalties," *Journal of Competition Law and Economics*, 2013, *9* (4), 931–1055.

_ , "The meaning of FRAND, Part II: injunctions," *Journal of Competition Law and Economics*, 2015, *11* (1), 201–269.

Siebrasse, Norman V and Thomas F Cotter, "The Value of the Standard," *Minn. L. Rev.*, 2016, *101*, 1159.

Singh, Nirvikar and Xavier Vives, "Price and Quantity Competition in a Differentiated Duopoly," *RAND Journal of Economics*, 1984, pp. 546–554.

Swanson, Daniel G and William J Baumol, "Reasonable and Nondiscriminatory (RAND) royalties, Standards Selection, and Control of Market Power," *Antitrust Law Journal*, 2005, *73* (1), 1–58.

Thomson, William, "On the Axiomatics of Resource Allocation: Interpreting the Consistency Principle," *Economics and Philosophy*, 2012, *28* (03), 385–421.

Tirole, Jean, *The Theory of Industrial Organization*, MIT press, 1988.

U.S. Department of Justice and Patent & Trademark Office, "Policy Statement on Remedies for Standards-essential Patents subject to Voluntary F\RAND Commitments," January 2013. Available at https://www.uspto.gov/about/offices/ogc/Final_DOJ-PTO_Policy_Statement_on_FRAND_SEPs_1-8-13.pdf.

Vives, Xavier, *Oligopoly Pricing: Old Ideas and New Tools*, MIT press, 1999.

Appendix: Proof of Proposition

A Proposition 1

When firms are symmetric $u_i(D) = \bar{u}(D)$ for all $D \subseteq R$ and $i \in N$. Indeed, since all firms have access to the same (sub)set of technologies they face the same production costs. As an industry, they further face the same market demand. Thus, in equilibrium all firms have the same profit. Consequently, for each firm the induced game $(R, u_i) = (R, \bar{u})$, making liabilities of the form (3), equal to $1/n$, for each firm, for each technology (SEP).

B Proposition 2

Given the inverse market demand function for firm $i \in N$ is $p = \alpha - \beta \sum_{k \in N} q_k$, the profit maximization problem for firm i is given by

$$u_i(D) = \max_{q_i} \pi_i(D) = (p_i - c_i(D))\, q_i = \left(\alpha - \beta \sum_{k \in N} q_k - c_i(D)\right) q_i,$$

where $k = 1, 2$ and $k \neq i$. The FOC for firm i is

$$\alpha - \beta \sum_{k \in N} q_k - \beta q_i(D) - c_i(D) = 0.$$

Solving all n FOCs, we have

$$q_i(D) = \frac{\alpha + \sum_{k \in N} c_k(\emptyset) - (n+1)c_i(\emptyset) + \left(n\theta_i - \sum_{k \in N \setminus \{i\}} \theta_k\right)\epsilon_D}{\beta(n+1)} \text{ and}$$

$$u_i(D) = \beta q_i^2(D) = \frac{1}{\beta}\left(\frac{\alpha + \sum_{k \in N} c_k(\emptyset) - (n+1)c_i(\emptyset) + \left(n\theta_i - \sum_{k \in N \setminus \{i\}} \theta_k\right)\epsilon_D}{n+1}\right)^2$$

The Shapley value for technology r_j is defined as

$$\begin{aligned} s_j(R, u_i) &= \sum_{D \subseteq R \setminus \{r_j\}} \frac{|D|!\,(n - |D| - 1)!}{n!} \left(u_i(D \cup \{r_j\}) - u_i(D)\right) \\ &= \frac{n\theta_i - \sum_{j \neq i} \theta_j}{(n+1)^2} \sum_{D \subseteq R \setminus \{r_j\}} \frac{|D|!\,(n - |D| - 1)!}{n!} \left(\epsilon_{D \cup \{r_j\}} - \epsilon_D\right)\left(q_i(D \cup \{r_j\}) + q_j(D)\right), \end{aligned}$$

so that the liability index is

$$
\begin{aligned}
& y_i\left(u, r_j\right) \\
& =\frac{s_j\left(R, u_i\right)}{\sum_{h \in N} s_j\left(R, u_h\right)} \\
& =\left(1+\sum_{h \in N \backslash\{i\}} \frac{n \theta_h-\sum\limits_{k \neq h} \theta_k}{n \theta_i-\sum\limits_{k \neq i} \theta_k} \frac{\sum\limits_{D \subseteq R \backslash\{r_j\}}|D|!(n-|D|-1)!\left(\epsilon_{D \cup\{r_j\}}-\epsilon_D\right)\left(q_h\left(D \cup\{r_j\}\right)+q_h(D)\right)}{\sum\limits_{D \subseteq R \backslash\{r_j\}}|D|!(n-|D|-1)!\left(\epsilon_{D \cup\{r_j\}}-\epsilon_D\right)\left(q_i\left(D \cup\{r_j\}\right)+q_j(D)\right)}\right)^{-1} .
\end{aligned}
$$

Under perfect compatibility, we have

$$
\begin{aligned}
& y_i\left(u, r_j\right) \\
& =\left(1+\sum_{h \in N \backslash\{i\}} \frac{n \theta_h-\sum_{k \neq h} \theta_k}{n \theta_i-\sum_{k \neq i} \theta_k} \frac{\sum_{D \subseteq R \backslash\{r_j\}}|D|!(n-|D|-1)!\left(q_h\left(D \cup\{r_j\}\right)+q_h(D)\right)}{\sum_{D \subseteq R \backslash\{r_j\}}|D|!(n-|D|-1)!\left(q_i\left(D \cup\{r_j\}\right)+q_i(D)\right)}\right)^{-1} .
\end{aligned}
$$

When $n=2$, we have

$$
y_i(u, r_j)=\left(1+\frac{2 \theta_k-\theta_i}{2 \theta_i-\theta_k} \frac{\sum_{D \subseteq R} q_k(D)}{\sum_{D \subseteq R} q_i(D)}\right)^{-1} \text { where } k=\{1,2\} \backslash\{i\} .
$$

When $\theta_1=\theta_2$, then we have

$$
y_i(u, r_j)=\left(1+\frac{\sum_{D \subseteq R} q_k(D)}{\sum_{D \subseteq R} q_i(D)}\right)^{-1} \text { where } k=\{1,2\} \backslash\{i\} .
$$

Furthermore if $c_i(D)=c_j(D)$ for all $D \subseteq R$, then $y_i(u, r_j)=\frac{1}{2}$.

C Proposition 3

Given the inverse demand function for firm $i=1,2$ is $p_i=\alpha_i-\beta_i q_i-\gamma q_k$ where $k \neq i$, the profit maximization problem for firm i is given by

$$
u_i(D)=\max_{q_i} \pi_i(D)=\left(p_i-c_i(D)\right) q_i=\left(\alpha_i-\beta_i q_i-\gamma q_k-c_i(D)\right) q_i
$$

The FOC is

$$
\alpha_i-2 \beta_i q_i(D)-\gamma q_k(D)-c_i(D)=0
$$

Solving the system, we have

$$q_i\left(D\right)=\frac{\left(2\alpha_i\beta_k-\alpha_k\gamma\right)-\left(2\beta_kc_i\left(D\right)-\gamma c_k\left(D\right)\right)}{4\beta_i\beta_k-\gamma^2}\text{ and }p_i=\beta_iq_i+c_i\left(D\right)$$

Hence

$$u_i\left(D\right)=\left(p_i-c_i\left(D\right)\right)q_i\left(D\right)=\beta_iq_i^2\left(D\right)$$

For technology 1, we have

$$\begin{aligned}s_1(R,u_i)=&\frac{1}{2}(u_i(\{r_1\})-u_i(\emptyset))+\frac{1}{2}(u_i(R)-u_i(\{r_2\}))\\=&\frac{((2-\beta_k^2)\theta_i-\gamma\theta_k)\left(\epsilon_{r_1}\left(q_i(\{r_1\})+q_i\left(\emptyset\right)\right)+\left(\epsilon_R-\epsilon_{r_2}\right)\left(q_1\left(R\right)+q_1(\{r_2\})\right)\right)}{2(4\beta_i\beta_k-\gamma^2)}.\end{aligned}$$

Thus, for technology r_j, we have

$$\begin{aligned}&y_i(u,r_j)\\=&\left(1+\frac{(\theta_k(2-\beta_i^2)-\gamma\theta_i)\left(\epsilon_{r_j}\left(q_k\left(\{r_j\}\right)+q_k\left(\emptyset\right)\right)+\left(\epsilon_R-\epsilon_{R\backslash\{r_j\}}\right)\left(q_k\left(R\right)+q_k\left(R\backslash\{r_j\}\right)\right)\right)}{(\theta_i(2-\beta_k^2)-\gamma\theta_k)\left(\epsilon_{r_j}\left(q_i\left(\{r_j\}\right)+q_i\left(\emptyset\right)\right)+\left(\epsilon_R-\epsilon_{R\backslash\{r_j\}}\right)\left(q_i\left(R\right)+q_i\left(R\backslash\{r_j\}\right)\right)\right)}\right)^{-1}\end{aligned}$$

Consider prefect compatible case such that $\epsilon_{12}=\epsilon_1+\epsilon_2$. Then we have

$$y_i(u,r_j)=\left(1+\frac{(\theta_k(2-\beta_i^2)-\gamma\theta_i)\sum_{D\subseteq R}q_k\left(D\right)}{(\theta_i(2-\beta_k^2)-\gamma\theta_k)\sum_{D\subseteq R}q_i\left(D\right)}\right)^{-1}.$$

D Proposition 4

Given the inverse demand for downstream firms $i\in L$ is $p=\alpha-\beta\sum_{k\in L}q_k$, the profit maximization problem for firm i is given by

$$u_i\left(D\right)=\max_{q_i}\pi_i\left(D\right)=(\alpha-\beta\sum_{h\in L}q_h-\sum_{h\in M}d_h-c_D)q_i.$$

The FOC for firm i is $\alpha-\beta\sum_{h\in L}q_h-\sum_{h\in M}d_h-c_D=\beta q_i$ so that solving l FOCs, we have

$$q_i\left(D\right)=\frac{\alpha-c_D-\sum_{h\in M}d_h}{\beta\left(l+1\right)}\text{ and }u_i\left(D\right)=\beta q_i^2\left(D\right)\text{ for all }i\in L.$$

By backward induction, the profit maximization problem for the upstream firm $k \in M$ is given by

$$u_k(D) = \max_{d_k} \pi_k(D) = d_k \sum_{h \in L} q_h(D).$$

The FOC for firm $j \in M$ is $\alpha - c_D - \sum_{k \in M} d_k = d_j$ so that we have

$$d_j = \frac{\alpha - c_D}{m+1} \text{ and } u_j(D) = \frac{l}{\beta(m+1)^2(l+1)}(\alpha - c_D)^2 \text{ for all } j \in M.$$

Therefore, we have

$$u_i(D) = \frac{1}{\beta(m+1)^2(l+1)^2}(\alpha - c_D)^2 \text{ for all } i \in L.$$

For downstream firms $i \in L$, the Shapley value for (R, u_i) for technology $r_j \in R$ is

$$\begin{aligned} s_j(R, u_i) &= \sum_{D \subseteq R \setminus \{r_j\}} \frac{|D|!(n - |D| - 1)!}{n!}(u_i(c_{D \cup \{r\}}) - u_i(c_D)) \\ &= \frac{1}{\beta(m+1)^2(l+1)^2} \sum_{D \subseteq R \setminus \{r_j\}} \frac{|D|!(n - |D| - 1)!}{n!} \left[(\alpha - c_{D \cup \{r\}})^2 - (\alpha - c_D)^2\right]. \end{aligned}$$

and for upstream firms $k \in M$, the Shapley value for (R, u_k) technology $r_j \in R$ is

$$\begin{aligned} s_j(R, u_k) &= \sum_{D \subseteq R \setminus \{r_j\}} \frac{|D|!(n - |D| - 1)!}{n!}(u_j(c_{D \cup \{r_j\}}) - u_j(c_D)) \\ &= \frac{l}{\beta(m+1)^2(l+1)} \sum_{D \subseteq R \setminus \{r_j\}} \frac{|D|!(n - |D| - 1)!}{n!} \left[(\alpha - c_{D \cup \{r_j\}})^2 - (\alpha - c_D)^2\right]. \end{aligned}$$

Hence, for each technology $r_j \in R$, we have for each downstream firm $i \in L$

$$\begin{aligned} y_i(u, r_j) &= \frac{s_j(R, u_i)}{\sum_{h \in L} s_j(R, u_h) + \sum_{h \in M} s_j(R, u_h)} \\ &= \frac{\frac{1}{\beta(m+1)^2(l+1)^2}}{l\frac{1}{\beta(m+1)^2(l+1)^2} + m\frac{l}{\beta(m+1)^2(l+1)}} = \frac{1}{l(m(l+1)+1)}, \end{aligned}$$

and for each upstream firm $k \in M$

$$
\begin{aligned}
y_k(u, r_j) &= \frac{s_j(R, u_k)}{\sum_{h \in L} s_j(R, u_h) + \sum_{h \in M} s_j(R, u_h)} \\
&= \frac{\frac{l}{\beta(m+1)^2(l+1)}}{l \frac{1}{\beta(m+1)^2(l+1)^2} + m \frac{l}{\beta(m+1)^2(l+1)}} = \frac{l+1}{m(l+1)+1}.
\end{aligned}
$$

E Proposition 5

Given the inverse demand for downstream firms $i = 2, ..., n$ is $p_i = \alpha - \beta q_i - \gamma \sum_{h \neq 1,i} q_h$, the profit maximization problem for firm i is given by

$$
u_i(D) = \max_{q_i} \pi_i(D) = \left(\alpha - \beta q_i - \gamma \sum_{h \neq 1,i} q_h - c_D - d\right) q_i.
$$

The FOC for firm i is $\alpha - 2\beta q_i - \gamma \sum_{h \neq i,1} q_h - c_D - d = 0$ so that solving $n-1$ FOCs, we have

$$
q_i(D) = \frac{\alpha - (c_D + d)}{2\beta + n\gamma} \text{ and } u_i(D) = \beta q_i^2(D) \text{ for all } i \in L.
$$

By backward induction, the profit maximization problem for the upstream firm 1 is given by

$$
u_1(D) = \max_d \pi_1(D) = d \sum_{i \in L} q_i(D).
$$

The FOC is $\alpha - (c_D + 2d) = 0$ so that we have

$$
d = \frac{\alpha - c_D}{2} \text{ and } u_1(D) = \frac{(\alpha - c_D)(n-1)}{4(2\beta + n\gamma)}.
$$

Therefore, we have

$$
u_i(D) = \frac{\beta(\alpha - c_D)^2}{4(2\beta + n\gamma)^2} \text{ for all } i \in L.
$$

For downstream firms $i \in L$, Shapley value for (R, u_i) with respect to technology r_j is

$$
\begin{aligned}
s_j(R, u_i) &= \sum_{D \subseteq R \setminus \{r_j\}} \frac{|D|!(n-|D|-1)!}{n!} (u_i(c_{D \cup \{r_j\}}) - u_i(c_D)) \\
&= \frac{\beta(\alpha - c_D)^2}{4(2\beta + n\gamma)^2} \sum_{D \subseteq R \setminus \{r_j\}} \frac{|D|!(n-|D|-1)!}{n!} \left[(\alpha - c_{D \cup \{r_j\}})^2 - (\alpha - c_D)^2\right].
\end{aligned}
$$

and for the upstream firm, the Shapley value for (R, u_1)

$$\begin{aligned} s_j(R,u_1) &= \sum_{D\subseteq R\setminus\{r_j\}} \frac{|D|!(n-|D|-1)!}{n!}(u_1(c_{D\cup\{r_j\}})-u_1(c_D)) \\ &= \frac{(n-1)\left(\alpha-c_D\right)^2}{4\left(2\beta+n\gamma\right)} \sum_{D\subseteq R\setminus\{r_j\}} \frac{|D|!(n-|D|-1)!}{n!}\left[(\alpha-c_{D\cup\{r_j\}})^2-(\alpha-c_D)^2\right]. \end{aligned}$$

Hence, for each technology $r_j \in R$, we have for each downstream firm $i \in L$

$$\begin{aligned} y_i\left(u,r_j\right) &= \frac{s_j\left(R,u_i\right)}{\sum_{h\in L} s_j\left(R,u_h\right)+s_j\left(R,u_1\right)} \\ &= \frac{\frac{\beta(\alpha-c_D)^2}{4(2\beta+n\gamma)^2}}{(n-1)\frac{\beta(\alpha-c_D)^2}{4(2\beta+n\gamma)^2}+\frac{(n-1)(\alpha-c_D)^2}{4(2\beta+n\gamma)}} = \frac{\beta}{(n-1)\left(3\beta+n\gamma\right)}, \end{aligned}$$

and for the upstream firm 1, we have

$$\begin{aligned} y_1\left(u,r_j\right) &= \frac{s_j\left(R,u_1\right)}{\sum_{h\in L} s_j\left(R,u_h\right)+s_j\left(R,u_1\right)} \\ &= \frac{\frac{(n-1)(\alpha-c_D)^2}{4(2\beta+n\gamma)}}{(n-1)\frac{\beta(\alpha-c_D)^2}{4(2\beta+n\gamma)^2}+\frac{(n-1)(\alpha-c_D)^2}{4(2\beta+n\gamma)}} = \frac{2\beta+n\gamma}{3\beta+n\gamma}. \end{aligned}$$