An Economic Perspective on Auctions*

Philippe Jehiel and Benny Moldovanu†

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Abstract

We study the role of auctions and market design in economic environments, and point out several main criteria for the design of successful auctions. In particular, we review the achievements of auction theory while pointing out the complex issues and limitations arising in practical applications. In Sections 1 and 2 we describe the role of auctions and market design versus the classical competitive analysis, and the main reasons why auctions are used. In Section 3 we study the basic features of economic problems (e.g., as represented in demand and supply functions) that influence auction performance. In Section 4 we review the main results of auction theory, with special emphasis on the difficulties posed by multi-object auctions. In Section 5 we describe the new strategic effects arising in auctions that are followed by some interaction among the agents, and the tension arising between various goals in such frameworks. In Section 6 we apply these insights to the recent European UMTS license auctions. In Section 7 we draw the main lessons.

Contents

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†P. Jehiel: CERAS-ENPC and UCL; B.Moldovanu: University of Mannheim

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1 Markets and Efficiency

The quest for allocative efficiency when resources are scarce is one of the major themes of all economics. The Pareto criterion requires that the outcome of a market transaction has the property that no alternative outcome could improve the welfare of every participant. Under certain conditions (the most important being the absence of external effects), the Walrasian (or competitive) equilibrium is Pareto-optimal. But how markets are precisely organized to determine prices and trades is not explicitly addressed by that classical theory.

The powerful (but somewhat vague) idea that frictionless production and exchange by buyers and sellers will result in a competitive equilibrium (and thus in an efficient allocation of resources) is based on two important implicit assumptions: 1) Large numbers of traders: to avoid the excise of monopoly power, which leads to well-known inefficiencies, there must be sufficiently many buyers and sellers, so that no individual agents can significantly influence prices. 2) No externalities. If some agents are directly influenced by the allocation of goods to other agents, the description of the relevant goods needs to include the identity of the consumer, thus giving rise to a multitude of markets for personalized goods (and a multitude of personalized prices).

Frequently, the assumptions above are not fulfilled. Many trading situations are oligopolistic, and the participants are well aware of their market power. Moreover, personalized markets and pricing are rarely available in practice (even if they were, these markets would be obviously plagued by the absence of large numbers of traders). Standard "competitive" pricing necessarily leads then to inefficiencies since external effects are not taken into account. Just to take an example, a national sale of spectrum frequencies involves a unique seller and a few oligopolistic firms who act as potential buyers. Selling a license to a new entrant (say) will considerably decrease the expected profit of an incumbent, thus affecting its behavior. On the other hand, allowing the incumbent to remain a monopolist will negatively affect the consumers. How should the "market" decide which alternative is better by setting a "right" price for the license ? Monopoly (or oligopoly) power and externalities are unavoidable in this case, and in many other circumstances of interest. In this pervasive set-up, the objective of economic analysis becomes how to minimize the distortionary effects of the participants' influence on prices and allocations. Thus, one needs to carefully take into account the respective market institutions and the strategic incentives they offer to various participants.

Even when the "large numbers" and "no externality" assumptions needed to sustain the Walrasian analysis are not fulfilled, some economists, bureaucrats and politicians think that "the market will take care of it", and that "market design does not matter". This view is mostly based on the so-called "Coase Theorem" (although Coase himself should not necessarily bear responsibility for this prevalent interpretation). In Stigler's formulation, the Coase Theorem says that, no matter what the initial allocation of property rights is, if allowed to work properly, markets will resolve all problems of externalities and lead to an efficient outcome (since otherwise the agents will always be able to implement a better outcome by buying, selling and swapping the respective goods or property rights). But we all know from Akerlof's celebrated "lemons" example that the market (i.e, the competitive outcome) may completely fail to deliver efficiency if some agents possess information that is relevant to others. How is this private information (on which the owner has monopoly power) to be traded in the "market" ? Similarly, the large body of work following the analysis of Myerson and Satterthwaite (who study general trading mechanisms among privately informed agents) teaches us that the initial allocation of property rights influences the final outcome, and that, for some initial allocations, inefficiency with positive probability is unavoidable, no matter what negotiation mechanism is used. It is a mistake to think that these phenomena are not relevant for the real world, and that we should neglect their lessons. Even under complete information, Jehiel and Moldovanu (1999) have shown that resale markets (which indeed remove the final outcome's dependency on the initial allocation of property rights) need not lead to an efficient allocation if the parties in each exchange cannot write contracts that fully control the use of the resources by all future potential owners (which may not even be parties in the current transaction).

2 Auctions and Market Design

Since each market process creates specific strategic incentives for the participants, (and therefore leads to specific distortions once these participants have market power), it becomes necessary, both for a theoretical analysis and for practical applications, to pay more attention to the details of the market rules used to obtain prices and allocations. In particular, it is necessary to explicitly take into account the information available to each market participant. Like monopoly rents, information rents are prevalent in practice.

The performance of various market rules under explicit consideration of strategic aspects stemming from the exercise of market power is, roughly speaking, the main subject of the large body of theoretical and practical work known under the name of "Auctions and Mechanism Design" . Thus, this body of work is a natural complement to the traditional Walrasian analysis, and constitutes one of the pillars of modern economics.

Auctions have been continuously used since antiquity[2], and they remain simple and familiar means of conducting multilateral trade. It is widely believed that auctions yield efficient allocations (see Sections 4 below for several important theoretical results and caveats). Accordingly, the quantity and value of goods traded by auction is enormous (e.g., treasury auctions, spectrum auctions, private and government procurement auctions, CtoC, BtoC and BtoB internet auctions, real-estate auctions, and so on...; some important market procedures, such as takeover battles, combine auction features with some form of negotiation).

In an auction the participants submit "bids", which represent their demand or supply functions, and then accepted trades that must equate demand and supply and transaction prices are calculated by some explicit aggregation procedure (or formula). In some dynamic procedures, the traders observe others' bids and have the opportunity to repeatedly revise their own bids before the final outcome is reached. Thus, auctions directly implement the ideas implicit in the Walrasian analysis, and the "Walrasian auctioneer" looses its "deus ex machina" status.

In this article we will use the word "auction" to represent a specific set of rules that determines what bids can be made and how these bids are aggregated to yield prices and allocations. Intuitively, for most practical applications this set of rules (which needs to be specified in advance) must be relatively simple: the rules should not depend on the particular features of each instance where they are applied, and they should not depend on information that is not readily available to the auction's organizer. For example,

[2] See Shubik (1983) for an historical sketch.

consider the following auction rules for selling one indivisible object (say a house): all interested buyers send a bid in a sealed envelope. After all bids have been collected and opened, the house is awarded to the agent that made the highest bid, and the winner pays to the seller a price equal to her own bid. Obviously, in order to conduct this so-called first-price sealed-bid auction, the seller need not know any details about the buyers' identities, their valuations for the house, their beliefs about valuations of competitors, etc... Moreover, the same rules can be used for selling a great variety of other objects.

For various theoretical reasons it is sometimes necessary to consider allocation procedures (which will be called here "mechanisms") whose rules depend on additional features, particular to each instance of application. By using the above first-price sealed-bid auction the seller cannot obtain the highest possible price at which demand is less than, or equal to supply. That price is equal to the highest willingness to pay, which will tend to be higher than the highest bid (since bidding the true willingness to pay will always result in zero profits for the respective bidder). If the seller happens to know the willingness to pay of the various potential buyers, he should of course make a take-it-or-leave-it offer to the buyer with the highest willingness to pay (at a price slightly below that willingness to pay). But, generally, such a set of rules is obviously silly since its implementation relies on details (the identity of the best buyer and his willingness to pay) which are usually not known ex-ante. Trying to apply it in practice will yield a take-it-or leave-it offer to a "random" buyer at a "random" price, and will in most cases perform markedly worse than the auction that yields, in expectation, a price equal to the second-highest willingness to pay. Of course, the vast body of work on mechanism design[3] is not about "silly" mechanisms, but nevertheless considers features (such as bidder-specific reserve prices or handicaps which are based on subjective information about bidders' values) that go beyond the intuitive, lay-man interpretation of what an "auction" is (but we warn the reader that the distinction is not sharp, and that it is notoriously difficult to formalize).

2.1 Auctions' Goals

So far, we have motivated the theoretical and practical interest in auctions by focusing on efficiency considerations. In practice, however, auctions are often used in order to achieve important goals, besides, or instead efficiency. We list below several other goals that are often used to justify the use of

[3] See Jackson (2000) for an insightful survey of some main results.

auctions in particular instances:

1. Revenue-maximization. The seller of an item at eBay probably does not care much about allocative efficiency, but rather aims at maximizing the price he gets (analogously, a buyer in a procurement situation wants to minimize the price he pays for the bought goods or services). Auctions are centered around the notion of competition among bidders, and in most situations this competition has a clear positive effect on the collected revenue. In the case of privatization exercises (such as the sale of licenses) it is claimed that revenue collected at auctions is a form of taxation that is less distorting than other, more traditional methods.

2. Information Aggregation and Revelation. Besides allocating scarce resources, auctions aggregate bids which are made based on the basis of privately known demand and supply functions. Hence, the resulting prices can also be seen as aggregators of private information. In some important auctions, this informational function is paramount. For example, the data collected at the periodical auctions of liquidity organized by central banks is an important indicator for future monetary policy. Related to this goal, we also have:

3. Valuation and Price Discovery. Many objects (e.g., works of art, particular pieces of real-estate, patented innovations, spectrum licenses) lack close substitutes that can be traded in a competitive market. It is then impossible for the owner to set appropriate prices reflecting "true value". Auctions are then simple and effective methods for valuation. Bidders can also learn from auctions: it is rarely the case that buyers, say, enter an auction with a fixed value for the item sold. Rather, the agents learn from each other's bidding (especially in some forms of dynamic auctions) and adjust their valuations accordingly. This feature is particularly important if future resale is a possibility, or if the bidders are also active in related markets. For example, daily trading in some financial markets that are organized around an order book and continuous trading often starts with an explicit auction phase that sets the "opening" prices.

4. Transparency and Fairness. In serious auctions the rules are precise, fixed in advance, and applied equally to all participants. As a result, auctions can withstand public or legal scrutiny better than other allocation procedures (such as beauty contests, or amorphous negotiations) whose rules are not made explicit. Moreover, transparency limits the

possibilities of corruption in the instances where some participants are represented by agents.

5. Speed and Low Administrative Costs. Auctions provide the means for achieving quick, frictionless transactions (as opposed to multilateral negotiations). Speed is particularly important for perishable goods such as fish, vegetables or flowers. Accordingly, most whole-sale markets for agricultural products have long been organized as auctions. The need to save on administrative costs is a major feature in privatization and in procurement (public or private).

6. Fostering Competition. In privatization environments, state-owned assets are often re-allocated via auction-like procedures since other methods (such as beauty contests and comparative hearings) are prone to lobbying and corruption, or are plainly inefficient (e.g., lotteries). If the auctions are correctly devised, it is possible to ensure that the previous (often monopolistic) market structure is replaced by a more competitive one. The creation of new market architectures where several firms compete has been accompanied by the creation of auction-like market places (e.g., for electricity and gas). These market-places mimic to some extent the well-established stock exchanges, while taking into account the special properties of the traded goods, which are often much more complex than common stock. If a private monopoly is not avoidable (in cases where production is a "natural monopoly") entrenchment can be avoided by limiting the period for which the rights to use the public assets are valid, and by using auctions repeatedly.

The above goals are not independent of each other. Depending on the economic environment and on the market process, there are subtle relations among them, and sometimes even severe conflicts (which will be discussed in more detail in Sections 4 and 5).

Thus, the first rule for practical auction design is to clearly identify the auction's main goal (or combination of goals). Usually, some trade-offs with respect to other goals will have to be made. The "mechanism design" body of work (which, as we noted before, considers also theoretical trading mechanisms that are far from our common-sense intuition about "auctions") is important precisely because it points out the theoretical limitations and trade-offs inherent in any market design exercise.

3 Economic Features that Influence Auctions' Outcomes

We focus below on auctions where objects are bought, i.e., the active group of agents reveal information about their demand functions, while supply is exogenous. Auctions where bidders express their willingness to supply are analogous. We do not address here the important issues specific to two-sided auctions (about which there is less theoretical knowledge)

Besides the obvious dependence on the auction's rules, the most important determinants of theoretical auction performance are related to the economics of demand (or supply, in procurement) in the underlying situation. The respective features influence the strategic behavior of the various participants, and ultimately the outcome. Without being exhaustive, we list below several main properties, and briefly mention the channels through which they influence strategic behavior:

1. Informational Externalities. We say that the economic situation displays informational externalities if the valuation of one agent depends on information available to another agent, i.e., the valuations contain common components. For example, consider two firms that bid for an oil field. If one firm has an adjacent field, and has already conducted a geological survey, the information contained in the survey affects the valuations of both firms. In a sealed-bid auction each firm needs to make a bid based on its own information. Thus, the information affecting the other firms cannot be aggregated (since by the time the bids are opened the auction is over), and inefficiencies occur. This suggests that informational externalities call for "open" bidding formats where bidders learn from each others' bid, and can always react to other bids. On the other hand, open formats where information is gradually revealed via bids can serve collusive purposes.

2. Allocative Externalities. We say that the economic situation displays allocative externalities if the valuation of one bidder depends on the entire allocation of physical goods and money to herself and to other bidders (whereas without allocative externalities, bidders care only about their own allocation and expenditure). Allocative externalities arise in any situation where the auction is followed by, and influences, some form of interaction among potential bidders (e.g., a secondary market). For example, in a license auction, the valuation of a monopolist incumbent may depend on whether one or two licenses are sold. In the latter case entry may occur, with an adverse effect on the monopolist's future

profits (even if the incumbent also acquires a license). In a patent auction for a cost-reducing innovation, a loosing firm may care about which of its competitors has acquired the patent and how much it has paid for it (since the nature of future competition will be affected by that). Accordingly, a firm may be willing to spend considerable amounts of money in order to buy a patent which has no value to it , but only if this means that the patent will not fall in the hands of another firm - this induces shelves full of "sleeping" patents.

3. Homogeneity/Heterogeneity of Goods. In an auction where several objects are sold, we say that the objects are homogenous if they are indistinguishable from each other. Otherwise, objects are heterogenous. Together with the next two properties that describe how many units a buyer demands, and how the units are related to each other, this differentiation is important for the decision whether to sell the objects separately in multiple auctions, or jointly in a single auction.

4. Unit Demand/Multi-unit Demand. We say that bidders have unit demand if, in a multi-unit (or multi-object) auction, their demand is satiated after they acquire one object. Otherwise, we say that bidders have multi-unit demand. A main strategic incentive created by multi-unit demand, which leads to inefficiencies, is the so-called "demand reduction" phenomenon (see Section 4.2.1 below).

5. Complementarity/Substitutability among Goods. In an auction where several objects are sold and demand is of the multi-unit form, we say that the objects are complements [substitutes] if the value attached to a bundle is higher [lower] than the sum of the values attached to the individual objects in the bundle. The usual scenario where bidders derive decreasing marginal utility from additional units (with single unit-demand as an extreme form) is covered by the definition of substitution. Complementarities arise when there are synergies among the objects: think for example about two regional broadcasting licenses that offer together national coverage. It is worth noting here that competitive equilibria with indivisible goods and complementarities do not generally exist.

6. Budget Constraints. In many situations bidders face some form of financial constraints (e.g., absolute budget limits, increasing marginal cost of financing, etc...) Intuitively, auction formats that encourage lower bids will be less affected by these constraints, and therefore such schemes may ultimately perform better (both in terms of efficiency and

revenue) than other auction formats where the unconstrained bids are higher.

7. Risk Aversion. From the point of view of an individual bidder, an auction resembles a lottery since the probability of winning is not known, and it is usually less than one. Some auction formats implicitly offer some "insurance" against losing, thus causing risk-averse bidders to bid higher. An example of this phenomenon is the fact that the sealed-bid first-price auction yields a higher revenue than the sealed-bid second-price auction if bidders are risk averse.

8. Bidder Symmetry. We say that bidders are (ex-ante) symmetric if their utility functions have the same functional form, and if they have the same beliefs about each other. Many of the classical results of auction theory are obtained under this assumption, and are very sensitive once one abandons it. Especially when the number of bidders is small, asymmetries tend to play a big role (for the diminished role of asymmetries in large auctions see Swinkels (1999), (2001))

The second rule of practical auction design is to identify what various bidders want to achieve, and what are the precise features of the economic situation that will potentially influence bidders' behavior. Only by choosing an auction format that takes into account these issues, will it be possible to attain the auction's goal.

Even the "mere" decision about what objects to auction can have far reaching consequences. While the Mona-Lisa is a Mona-Lisa, in some of today's complex markets the physical definition of the traded objects is not a-priori clear. Demand or supply functions depend on many factors (with varying importance for different agents). Hence the precise structuring of the traded goods and bids play a main role in determining whether the auction procedure can accurately represent the agents' preferences. For example, in most European UMTS auctions (except Germany and Austria), the auctioned objects were licenses with a predefined (possibly different) spectrum capacity, and a bidder was allowed to buy at most one license. Hence we had a situation with unit demand and heterogenous objects. In contrast, in the German and Austrian design (who had the same goal as all other 3G allocation procedures - to create an efficient market for next-generation mobile telephony), the auctioned objects were identical blocks of spectrum capacity, a variable number of which needed to be aggregated in order to create large or small licenses. Hence, the situation was one of multi-unit demand, homogenous objects, and complementarities (see Section 6 for more details). For another example, consider electricity exchanges: in the English market (which is currently re-organized) operators bid for the right to supply electricity next day, and they are allowed to place several bids, one for each generating unit they possess (e.g., nuclear reactor, coal-plant, gas-turbine, etc...). In contrast, in the German exchange LPX (which is currently being merged with the other marketplace, EEX) operators place bids that are independent of the generating unit, but have the choice among specific periods of time during the next day (e.g., "night", high-noon", "rush-hour", etc...).

4 A Review of Basic Results

We now review some basic results in auction theory[4]. Till recently, attention has mostly been devoted to the study of single object auctions, which we address first.

4.1 Single-Object Auctions

4.1.1 The Private Values Paradigm

The simplest setup is one in which bidders know how much they value the good for sale, but are uncertain as to how much other bidders value the good. This is the so-called private value paradigm.

The ascending price (or English) auction is such that the price gradually increases, bidders may drop out at any point in time, and the auction stops when there is only one bidder left. The last active bidder buys the good at the price where the auction stopped. In the private value setting, the ascending price auction induces an efficient outcome, no matter whether bidders are ex-ante symmetric or not, and no matter what the risk attitude of the bidders is. The reason is that it is a dominant strategy to drop out whenever the price reaches one own's valuation. Vickrey (1961) proposed a condensed version of this auction, now called the Vickrey auction or, in the context of one-object auctions, the sealed-bid second-price auction, in which agents secretly place bids. The bidder with the highest bid wins the object and pays the second-highest bid. Vickrey observed that in the second-price sealed-bid auction it is a dominant strategy to bid one own's valuation. Hence this format is here equivalent to the ascending price auction.

Beyond the efficiency properties of ascending price and second-price sealed-bid auctions, are these formats good at generating revenues? As shown by

[4]Valuable surveys of the auction-theoretic literature are: Milgrom (1985, 1987), Mc Afee and McMillan (1997), Wilson (1993), Wolfstetter (1996) and Klemperer (1999). Kagel (1995) surveys the extensive experimental research on auctions.

Myerson (1981) and Riley and Samuleson (1981), it turns out that these formats are also revenue maximizing whenever bidders' signals about their values are independent of each other, agents are risk neutral, ex-ante symmetric, and the seller is bound to sell her good. And if the seller may retain her good, the optimal mechanism is also such an auction augmented by a reserve price or an entry fee.

Practitioners are sometimes puzzled by the optimality of the second-price sealed-bid auction[5]. They feel that more money could be extracted by requesting that the winner pays the highest bid, rather than the second highest bid. Such a format corresponds to the more commonly used first-price sealed-bid auction. The argument ignores that bidders react to a change of format by adjusting their bidding strategies. In a first-price auction, a bidder who bids her own value never makes any money. Hence bidders will bid less than their value, and bids will be lower than in the second-price version (but the seller receives the highest bid, not the second highest). It turns out that, in expected terms, the first-price auction generates exactly the same amount of revenue as the second-price auction as long as the agents are symmetric and risk neutral, and obtain independent signals about their respective values. The same holds for other standard formats such as the descending price (or Dutch) auction where the prices decreases from a high level till one bidder stops the auction and buys the good at the respective price, or the all-pay auction where the highest bidder wins the object but all bidders pay their bid ! This result is the celebrated Revenue Equivalence Theorem, first noticed by Vickrey. It is also the case that, in symmetric settings, all standard formats allocate the good efficiently to the bidder who values it most. This is not a coincidence. In fact, revenue equivalence is precisely derived from the fact that the allocation is the same in all standard formats (see Myerson (1981) and Riley and Samuelson (1981)).

4.1.2 Extensions

We want to stress again that the above strong conclusions heavily rely on ex-ante symmetry, risk-neutrality, the absence of budget constraints, signal independence, and the absence of informational or allocative externalities. Let us now relax these assumptions, one at a time:

1. Asymmetries: The optimal strategy in the second-price auction is a dominant strategy, and therefore it is not affected by changes in the competitors' valuations or beliefs. On the other hand, the equilibrium strategy in the first price auction crucially depends on beliefs,

[5] For an early use of such an auction see Moldovanu and Tietzel (1998).

and, in fact, we are not even able to explicitly calculate an equilibrium in most asymmetric situations. In any case, revenue equivalence between these standard formats breaks down without symmetry. While ascending price and second-price auctions continue to induce efficiency even if bidders are asymmetric, they are no longer revenue-maximizing (see Myerson 1981 for a characterization of the optimal mechanisms in asymmetric settings). First-price sealed-bid and descending price auctions are neither efficient nor revenue-maximizing. The revenue comparison between second-price and first-price sealed-bid auctions can go either way (see Maskin-Riley (2000)).

2. Risk-Aversion: The English ascending price and second price sealed-bid auctions are still efficient. But standard auctions such as the first-price or second-price sealed-bid auctions are no longer revenue equivalent . If bidders are risk-averse, the first price auction generates more revenue than the second price auction since raising a bid offers some insurance against losses (see Holt (1980) and Maskin and Riley (1984)).

3. Budget Constraints: As mentioned above, the presence of budget constraints favors auction formats that induce lower bids. Such bids are obviously less likely to be affected by the constraint. Thus the revenue in a first-price sealed-bid auction is higher than in the second-price auction (see Che and Gale (1998)). A special role is played here by the all-pay auction: for a fixed (symmetric) absolute budget constraint, this auction is both revenue-maximizing and welfare-maximizing, although clearly not fully efficient (see Laffont and Robert (1996), and Maskin (?))

4. Signal Independence: The efficiency of the ascending and second-price auction is not affected by correlations among signals. But these formats are no longer revenue-maximizing , nor are they revenue-equivalent to other standard formats. By adroitly using the existing (even very small) correlations, the seller can in fact obtain a price equal to the valuation of the highest bidder - but a complex mechanism is needed to achieve this feat, with features never seen in practice (see Myerson (1981) and Cremer and McLean, 1985, 1988)).

5. Informational Externalities: Models with interdependent values cover situations in which the valuations of a given bidder i does not solely depend on bidder i's private information (or signal), but also on the information held by other bidders j, $j \neq i$. In this context, the theory has identified an important phenomenon, the winner's curse (Wilson

1969): in order to bid optimally, a bidder should take into account the information revealed by the fact that he is the winner of the auction (i.e., the fact that all other bidders, whose information is relevant, have chosen to bid less !). Failure to do so results in overbidding at least when the number of bidders is sufficiently large, and it may result in negative expected payoffs. This observation implies that an ascending price format is qualitatively different from the other standard formats since it allows a gradual release of information, and the possibility to react to that information. When a higher signal of bidder j makes bidder i 's expected valuation for the good higher, Milgrom and Weber (1982) have shown in a symmetric setup that the ascending price auction generates more revenue than the second-price auction[6], and that the second-price auction generates more revenue than the first-price auction[7]. In the Milgrom-Weber symmetric setting, standard auctions are efficient if the agent with the highest signal (who always wins the auction) has also the highest value. This condition is satisfied if a mild "single-crossing" property is imposed: agent $i's$ signal must have a higher impact on $i's$ value than on $j's$ value, where $j \neq i$. Efficiency in interdependent value contexts with asymmetric bidders has recently attracted a lot of attention. In a two-bidders asymmetric setting, Maskin (1992) has noted that the ascending price auction continues to be efficient if the signal held by every bidder is one-dimensional[8] and if the single-crossing property is satisfied. Unfortunately, with more than two bidders, a much stronger single crossing property is required for the ascending price auction to be efficient[9].

6. Allocative Externalities. In single object auctions with physical externalities, losing bidders care about the identity of the winner. Hence their valuations for the object are not a-priori well-defined, and depend on their respective beliefs about potential outcomes. Different auction

[6]If bidders' valuations are not known initially but must be learnt by bidders, then the various auction formats are no longer equivalent even in a private value setting (see Compte-Jehiel 2002b who show the superiority of the ascending format in such a setting).

[7]Bulow and Klemperer (2002) address the robustenss of that conclusion in asymmetric setups.

[8]Impossibility results for the one-object, multi-dimensional case have been obtained by Dasgupta and Maskin (2000), and Jehiel and Moldovanu (2001).

[9]See Perry-Reny (2002) , and Krishna (2000) who extends a condition due to Kirchkamp and Moldovanu (2000). Compte-Jehiel (2002) offer examples in which the efficiency comparison between second price and ascending price auctions can go either way in interdependent value contexts with more than two bidders.

formats induce different beliefs and numerous new strategic effects (see also Section 5 below). In sealed-bid formats, agents must place a bid based on the expected (or average) externality, which is usually not equal to the realized externality. This leads to inefficiency even in ex-ante symmetric settings (see Jehiel, Moldovanu and Stacchetti, 1996, 1999; these authors also showed that revenue maximization calls here for special features such as entry fees that are dependent on the number of bidders, or payments to the seller even if she does not sell). We have identified above the well-documented role for ascending formats in situations with informational externalities. Interestingly, Das Varma (2000) shows that the ascending-price auction is not equivalent to a sealed-bid format even if (only) allocative externalities are present. The reason is that in the ascending format bidders can see who is still bidding and who left the auction, and adjust their beliefs accordingly. But not even the ascending-price auction is generally efficient, and revenue comparisons to sealed-bid formats can go both ways. Ettinger (2000) and Maasland and Onderstal (2001) have shown that first-price and second-price sealed-bid auctions are not anymore revenue equivalent if losing bidders care about the amount of money paid by the winner.

4.2 Multi-object auctions

Multi-object auctions raise a large number of additional difficulties. Even when externalities (allocative of informational) are absent, multi-unit demand, heterogeneity and complementarities induce complex demand functions, which are difficult to map in reasonably simple auction formats. Such formats necessarily restrict bidders in some aspects, creating complex strategic effects that affect the auction's performance. Even within the private values paradigm without any externalities there are only a few positive results:

1. If bidders have unit-demand and if the objects are homogeneous, a simple extension of the second-price sealed-bid auction, called the $(k+1)^{th}$ price auction (where k is the number of units for sale), induces an efficient allocation. This format is described as follows: agents simultaneously submit a bid for one unit; the bidders with the k highest bids win a unit each, and they each pay the same price, equal to the $k+1^{th}$ bid.

2. If bidders have unit demand and the objects are heterogenous, a simultaneous ascending-price auction is efficient (under some important behavioral caveats[10] !). In such an auction, prices are initially at a low level and bidders express demand by placing a bid on one of the objects. The prices of those objects that receive more than one bid are raised, and the procedure is repeated until demand equals supply (i.e, one unit) for each object.

3. If bidders have multi-unit demand, but there are no complementarities nor substitutability (i.e., valuations for bundles equal the sum of the valuations for the individual objects in the bundle), efficiency can be achieved by auctioning the objects in separate one-object auctions according to second price or ascending price auctions. It is important to mention that, even in this simple case, the revenue-maximizing auction is not known (see also Section 4.2.4 below).

Using a series of examples, we next illustrate several main problems induced by more complex demand structures.

4.2.1 Multi-Unit Demand and Demand Reduction

We have seen above that, with single unit demand bidders and with k homogeneous units, the $k + 1^{th}$ -price auction induces an efficient allocation. When bidders have multi-unit demand, a seemingly easy generalization of this format is the uniform-price auction: bidders submit demand curves (i.e., bids for 1 up to k units), and the units are allocated to maximize the values expressed by the submitted demand curves; every allocated unit is sold at the same price p, the minimum price where aggregate demand coincides with the number of supplied units k.

Unfortunately, if bidders have multi-unit demand, the uniform price auction may lead to an inefficient allocation. Bidders have an incentive to lower their demand on all units but the first one they acquire. In doing so, they affect downwards the selling price and pay a lower price on the remaining units (see Nousair (1995), Ausubel and Cramton (1998) , and Engelbrecht-Wiggans and Kahn (1998)). The following example illustrates the point:

Example 1 *There are three homogeneous units for sale and three bidders i =1,2,3. Bidders 2 and 3 are interested in one unit only; their valuations are* 1 *and* 0.25*, respectively. Bidder 1 is potentially interested in three units. His valuation is* 10 *for the first unit,* 5 *for the second, and* 2 *for the third.*

[10] See Demange, Gale and Sotmayor (1986), and Milgrom (2000). Gul and Stacchetti (2000) describe the difficulties with multi-unit demand.

Efficiency in the above example dictates that bidder 1 gets all three units. Bidders 2 and 3 have a dominant strategy - to bid their values for one unit. If bidder 1 expresses his true demand, the minimum price where demand equals supply is (slightly above) 1, and bidder 1's payoff is given by $10+5+2-3 = 14$. However, in the equilibrium of the uniform price auction, bidder 1 will decrease his demand to only two units (e.g., he will bid 15 for either two or three units). This lowers the selling price per unit to 0.25, yielding for bidder 1 a payoff of $10 + 5 - 0.5 = 14.5$. The allocation is inefficient since bidder 2 obtains one unit.

It is obvious that in any "pay your bid" type of auction (such as the discriminatory auction, which has the same allocation rule as the uniform auction, but each bidder pays his own bid on the units he obtains) agents have incentives to bid less than their values (even on the first unit). Thus, the discriminatory auction may also be inefficient.

In this context it is interesting to recall that the uniform-price auction has been hailed by famous economists (including Nobel prize winners) as the most suitable method for auctioning Treasury bonds. The argument was that the uniform-price auction carries over to the case of multiple units the desirable characteristics of sealed-bid second-price auctions (i.e, existence of dominant strategy, efficiency, etc...) Unfortunately, as we saw above, that argument is incorrect, and applies only to the case of unit-demand (hardly realistic for Treasury bonds !)

4.2.2 Complementarities and Exposure

Complementarities are particularly troublesome in standard auction formats where bids can be placed only on individual objects, but not on bundles (or packages). It is then clear that individual bids cannot fully reflect the magnitude of complementarity, creating inefficiencies. The theoretically correct way to deal with complementarities is to allow for "combinatorial" auctions where agents can place bids directly on bundles[11]. Forbidding such bids may give rise to the so called *exposure problem.* Cramton (1997) offers a simple example where, even under complete information, the absence of combinatorial bids leads to inefficient non-participation.

Example 2 *There are two parking slots, and two bidders. Bidder 1 has a car and a trailer, and he values the two parking slots together at $100, while attaching a value of zero to each individual slot. Bidder 2 has only a car and values any slot at $75. The value of two slots is also $75 for this bidder.*

[11] see Ausubel and Milgrom (2001) for an ascending version of combinatorial auctions.

Efficiency dictates that bidder 1 gets both slots. But if the auction format does not allow bids on the whole package of two slots, any positive bid on an individual slot exposes bidder 1 to the danger of obtaining only that slot alone - an alternative valued at zero. The only equilibrium in a simultaneous ascending auction without combinatorial bids is for the first bidder to drastically reduce demand by non-participation (since otherwise he needs to bid up to \$75 per slot in order to outbid the other player). Bidder 2 inefficiently wins a slot by placing a minimum bid on it. In the presence of incomplete information, bidder 1 will bid only if he attaches a sufficiently high probability to the event in which bidder 2 has a low valuation. If bidder 1 decides to bid (based on his information), and if it turns out that bidder 2 has a high value, bidder 1 will regret his decision ex-post.

4.2.3 Combinatorial Bids and Free-Riding

The above example suggests that combinatorial bids are necessary in order to deal with complementarities. The main problem with combinatorial auctions is that they may be very complex to conduct and participate at. In extreme cases with many bidders and objects, aggregating combinatorial bids in order to determine a desired (e.g., efficient) allocation constitutes a so-called "NP-hard problem" for which no reasonable algorithm (ie., an algorithm whose number of steps increases polynomially in the auction's parameters[12]). Besides the structural complexity arising in large auctions, combinatorial bids also induce some subtle strategic problems. Consider the following example of free-riding, adapted from Milgrom (2000)[13]:

Example 3 *There are two objects* 1 *and* 2 *and three bidders* $0, 1, 2$. *Bidder* 0 *values only the bundle* $\{1, 2\}$ *at* v^{12}. *Bidder* i *values only object* i *at* v^i. *Assume that* $v^1 + v^2 > v^{12}$. *Each bidder* i *simultaneously submits a bid* b_i *for whatever good or bundle she wishes. The goods are allocated so as to maximize the revenue generated by the bids, and each bidder pays for the goods he receives according to the bid he submitted ("pay-your-bid" auctions).*

Efficiency dictates that bidder i receives object i, $i = 1, 2$, But in equilibrium there will be a "war of attrition" between bidders 1 and 2. Instead of bidding up to v^1 on object 1, bidder 1 prefers to place a low bid on object 1 (say $v^{12} - v^2$), hoping that bidder 2 will make a high bid on object 2 (say v^2).

[12] see DeVries and Vohra (2000) for the computational aspects of such auctions

[13] Theorem 6 in Milgrom (2000) deals with a related example with no complementarities in which one equilibrium has the same feature (however, in another equilibrium, the outcome is efficient).

Similarly, bidder 2 prefers to place low bid (say $v^{12} - v^1$), hoping that bidder 1 will make a high bid on object 1 (say v^1). As a consequence, there is an equilibrium in mixed strategies where bidder 0 gets the bundle with positive probability.

4.2.4 The Tension between Efficiency and Revenue

We have seen above that in one-object symmetric settings, standard auctions are efficient and revenue-maximizing (at least if the seller is not allowed to retain the good). Thus, efficiency and revenue go hand in hand. This ceases to be true in multi-object settings, even if the situation is symmetric and there are no complementarities. The point has first been observed by Palfrey (1983) (see also Jehiel-Moldovanu 2001a for an explicit interpretation in terms of the conflict between efficiency and revenue, and a relation to the revenue equivalence theorem; note that this theorem implies that all efficient multi-object auctions yield the same revenue). Since the argument is exceedingly simple, it is worth it mentioning here.

Example 4 *Consider an auction for two objects A and B, and two bidders, 1 and 2. For both agents, the valuations for the bundle $\{A, B\}$ are given by the sum of the valuations for the individual objects, and assume these to be as follows*[14]*:*

$$\begin{aligned} v_1^A &= 10; v_1^B = 7 \\ v_2^A &= 8; v_2^B = 12 \end{aligned}$$

The value maximizing auction (which puts the objects in the hand of those who value them most) is simply given by two separate second-price auctions, one for each object. Then object A goes to bidder 1 for a price of 8, while object B goes to bidder 2 for a price of 7. Total revenue is 15. But, consider now a single second-price auction for the entire bundle $\{A, B\}$. Then the bundle will be acquired by bidder B, for a price of 17 ! Hence, revenue is higher in the bundle auction, but object A is mis-allocated. Such a phenomenon occurs as soon as bidders do not have single unit demand, and occurs in all (generic) situations where bidders do not have the same ranking of valuations over the various objects. The advantage of bundling disappears only if the number of bidders is sufficiently large[15] .

[14] To ensure the applicability of the revenue equivalence theorem, assume that valuations can take any value between 7 and 12, but that they are concentrated around the deterministic ones displayed in the main text.

[15] see Chakraborty (1999) for the intermediate cases between two and infinity

The revenue-maximizing multi-object auction is not yet known. As illustrated by the example above, the difficulty is to exactly identify the realizations of values where inefficiency increases revenue.

4.2.5 Efficiency and Informational Externalities

In private value settings (even when there are asymmetries, complementarities and allocative externalities), a famous mechanism due to Vickrey, Clarke and Groves can be used to produce an efficient outcome if bidders are risk neutral and if budget constraints are absent. This mechanism requires that the agents express in their bids the values attached to every possible allocation of objects among all bidders. The pricing scheme is rather complex: roughly speaking, for every acquired bundle, each bidder pays (up to a constant) an amount that corresponds to the value which is foregone by not allocating the bundle efficiently in the hypothetical situation where the respective bidder is not present. Given such "prices", bidders completely internalize the social value of their decisions, and an efficient outcome results.

The main problem with the VCG mechanisms is that, except in very special cases -see the beginning of our Section on multi-object auctions - they do not correspond to simple, intuitive auction formats[16]. The complexity of the VCG scheme is generally perceived as a major drawback by practitioners.

Another problem with VCG mechanisms occurs when informational externalities are present, i.e., when bidders' valuations depend on the signals received by others. This situation is very likely to occur in those contexts where market structure considerations matter (see next Section for an example).

Specifically, when valuations are interdependent and the signal of at least one bidder is multi-dimensional (e.g. in multi-object auctions the multidimensionality comes from the need to express valuations on several objects and bundles), no mechanism whatsoever can allocate the goods efficiently if either complementarities, substitutions, or allocative externalities are present[17] (see Jehiel-Moldovanu 2001). In other words, there is no general analog of the Vickrey-Clarke-Groves mechanism in the multi-object, interdependent valuation case. Moreover, the second-best mechanism is not yet known[18].

[16] Ausubel (1997) offers an ascending auction format that coincides with the VCG pricing scheme if there are no allocative externalities.

[17] i.e, efficiency can be achieved only if the objects can be sold in separate auctions without any welfare loss.

[18] This should be contrasted to the case where one object is auctioned, but bidders obtain a multi-dimensional signal. In that case full-efficiency is not possible (Maskin, 1992, Dasgupta and Maskin, 2000, Jehiel and Moldovanu, 2001) but the second-best mechanism is readily available.

5 Auctions and Market Structure

Auctions with allocative externalities cover situations in which bidders do not solely care about the goods they get, but they also care about the entire allocation of goods to other agents (see Jehiel and Moldovanu, 1996, 2000, and Jehiel, Moldovanu and Stacchetti, 1996,1999). This is particularly relevant in those contexts where, after the auction, there is an interaction among bidders. This is the case in virtually all large auction applications such as auctions for electricity, natural resources, government licenses, landing slots, and even Treasury bonds (where one large player may try to "corner" the secondary market). In an auction for mobile phone licenses, say, bidders do not solely care about whether or not they are licensed, but also about what who else is licensed (and with which spectrum capacity). They care about it because the auction structures the nature of competition on the future mobile phone market by determining (to a large extent) how many and which competitors a firm will have. Another good example is offered by the situation where several firm in one industry bid for another in a take-over contest. A focus on allocative externalities can easily explain the well-documented "take-over premium" by noting that a bidder may fear that it will incur a future loss (market share, profit, etc...) if another firm wins. Thus, bidders are willing to pay above the intrinsic value of the acquired firm in order to avoid those perceived future losses (see Jehiel and Moldovanu (2000) for a simple model, and Molnar (2000) for some empirical evidence.)

5.1 A Two-Ways Interaction

If the auction's allocation influences the equilibrium of an ensuing interaction, bidders will need to take this effect into account at the bidding stage. Thus, the channel of influence between auction and future interaction goes both ways: the auction's outcome influences the future interaction through the resulting allocation of assets, and the future interaction influences the auction's outcome through the participants' expectations about their payoffs in various future constellations. This is an important lesson for participants (designers and bidders) at large government-sponsored auctions.

When objects and bidders are heterogenous, the array of possible market structures is quite large. But the analysis of auctions with externalities is quite subtle even in one-object, complete information settings. One reason is that the notion of "valuation" is not well defined a-priori. Specifically, how much a bidder is ready to pay depends on his expectation about what will happen if he does not buy the object[19]. If he expects the winner to be a tough competitor , he will be ready to pay a high price; if he expects the winner to be a soft competitor, his willingness to pay will be low. In particular, the often repeated maxim "*Put the objects in the hand of those who value them most*" is not even well-defined in this context.

A general model focusing on the effects of market structure is as follows: There are n bidders and the set of auctioned objects is M. Let μ denote a partition of the set M. Whereas in "traditional" auction models bidders care only about which objects they get, here we need to assume that each bidder i is characterized by a value function π^i, which associates to each partition μ, a payoff given that partition, $\pi^i(\mu)$.

As shown in Jehiel-Moldovanu (1996), several new phenomena arise in standard auctions: 1) There may be several equilibria with different allocations; 2) The objects need not be allocated to the efficient buyers; 3) Bidders may have incentives not to participate at the auction since their mere decision to participate influences the willingness to pay of other bidders, and therefore the final outcome. The following stylized example illustrates these claims:

Example 5 *There are three firms bidding for a fourth in a takeover contest. Consider the following expectations about future scenarios in the post-takeover industry: due to synergies, each bidding firm expects to make an extra profit of π if it wins the contest; if firm 1 wins, firm 2 expects a relative decrease in profits of α (and vice versa); firm 3 expects a decrease in profits of $\gamma < \alpha$ if firm 1 or firm 2 wins; finally, firms 1 and 2 expect to be unaffected if 3 wins.*

From the firms' viewpoint (e.g. abstracting from consumers' surplus), the efficient buyer is firm 3 (since the other firms do not expect to suffer a loss in that scenario). Consider a first price sealed-bid auction: In one equilibrium, firm 3 indeed wins by bidding only π. But in another, firms 1 and 2, who are very afraid of each other, engage in a race and one of them wins by bidding up to $\pi+\alpha$. In that case, both firms suffer a loss of $-\alpha$! If firms 1 and 2 think that the expensive race is going to happen because they cannot coordinate (say due to lack of trust) to let 3 win, they will have incentives to commit not to participate at the auction in the first place. For example, if firm 1 withdraws, 3 necessarily wins since it is willing to bid up to $\pi+\gamma$, while firm 2 is willing to bid only up to π (since 1 poses no danger anymore). This scenario is, in fact, better for firm 1 than participating in the race with 2.

[19] Of course, in the auction's bidding equilibrium expectations have to be correct.

5.2 The Tensions between Value Maximization, Efficiency and Revenue

In addition to the above points, it should be noted that if the allocative externalities are due to market structure considerations, the notion of economic efficiency should not be solely based on considerations about firms' welfare (recall again the maxim "put the objects in the hands of those who value them most !"). Instead, the welfare considerations should also include the consumer's surplus in each possible future scenario. Since consumers usually do not participate at the auction, there is little hope that an auction design that does not explicitly take their concerns into account will generate a high total welfare. Specifically, there is a risk that some firms will use the auction as an instrument to increase market power, to the detriment of consumers. But, a more thoughtful design that addresses the consumers' interest may generate low revenue. To illustrate these claims, consider the following stylized example:

Example 6 *There are two licenses A and B for sale. There are two firms $i = 1, 2$ competing for the two licenses. Each firm i is allowed to buy both A and B. If firms 1 and 2 each buy one license, price-competition is assumed to drive profits down significantly (say to zero). If firm i buys both licenses, it earns monopoly profits π_i. We assume that $\pi_1 > \pi_2$.*

Consider the standard format where firms simultaneously submit two bids b_i^A, b_i^B for licenses A and B, respectively. Each license is allocated to the highest bidder on that license, who pays the bid. Since one license is worthless (as long as the other is also sold), it is readily verified that the outcome of this auction is that firm 1 gets the two licenses and pays π_2 for it. In other words, the auction selects a monopoly structure (in fact the most "efficient" monopoly, since $\pi_1 > \pi_2$). But the resulting market structure is not very competitive, and the outcome is not desirable from the consumers' viewpoint, nor (in most applications) from the total welfare viewpoint.

If the government decides that each firm can buy only one license, a duopoly may emerge (which is presumably better for consumers and total welfare) but the auction's revenue will be zero ! Of course, the example is extreme, but it clarifies why it is rather naive to judge an auction's outcome by the generated revenue for the government (this has been done in the context of the UMTS spectrum licenses by most of the media and even by some academic commentators).

Since the demand function induced by the presence of allocative externalities is rather complex, the question arises whether the auction design should allow increased flexibility in expressing these values. Of course, some flexibility is necessary because it allows the bidders to compete and to reveal how much they value the goods for sale. But allowing maximum flexibility need not be a good idea if market structure matters. The point is that increased flexibility can be used by bidders to increase market power (possibly to the detriment of non-participating agents). A good design must careful balance these two aspects. To illustrate the trade-off, consider the following example:

Example 7 *There are four identical blocks of spectrum for sale. There are five potential bidders who compete for these blocks. In order to operate, a bidder needs one block, but bidders may buy up to 2 blocks. Each bidder i submits a bid schedule $b_i = (b_i(1), b_i(2))$. Blocks are allocated and payments are made according to a uniform price auction*[20]*. We denote by $\pi(k, n)$ the value of having k blocks in market with n operators*[21]*.*

Suppose that $\pi(2, 2) - \pi(1, 3) > \pi(1, 3)$. Then, an equilibrium outcome is one where two firms buy two blocks each, and the equilibrium price for a block is (slightly above) $\pi(1, 3)$ (so the winners pay $2\pi(1, 3)$ each. Flexibility (i.e., whether bidders acquire one or two blocks) leads here to a configuration with two large capacity operators. Whether or not this is a desirable outcome depends on the forces driving the comparison between $\pi(2, 2) - \pi(1, 3)$ and $\pi(1, 3)$. If the additional capacity (i.e. a change from $k = 1$ to $k = 2$) is what creates most value for the firms, then flexibility seems desirable. If, on the other hand, the extra value is created by market structure considerations (i.e, the increased market power in a market with only two competitors versus a market with more firms) then, presumably, flexibility harms consumers[22].

Market structure considerations also lead to "wars of attrition", as illustrated below:

Example 8 *There are 12 blocks of spectrum for sale. There are two strong incumbents who are already operating on the market, two weak incumbents, and two potential entrants. Bidders must buy two or three blocks to get a license. A uniform price auction is used to allocate blocks.*

[20] Given the demand schedules, the equilibrium price is where demand equals the supply of five blocks. The winners are those bidders that bid above that price (but all pay the same equilibrium price).

[21] In order to simplify the example, we neglect here the fact that an operator may also care about the precise distribution of the remaining blocks among competitors.

[22] From an econometric viewpoint, if the only available data are the bids of the firms, it is not possible to disentangle the two forces, and there is an identification problem. This observation suggests that one needs to look for additional data about the payoff sensitivity to a change in the market structure and/or the technological gain induced by extra capacity.

Suppose that acquiring three blocks is not valuable *per se,* but rather because it may induce a more concentrated market structure. The incumbents would like to avoid entry, but it is enough that three of them bid for three blocks. Each incumbent would like to avoid entry, but prefers that the others pay the higher price for three blocks. As a result of this free riding incentive, in equilibrium an entrant may acquire a license with positive probability.

5.3 Information and Market Structure

So far we have focused on the relations between market structure considerations and allocative externalities. But there are also strong relations to informational externalities (see Jehiel and Moldovanu, 2000, 2001). To illustrate this, suppose that two licenses A and B (possibly with different capacities, or coverages, or other technical attributes) are auctioned, and suppose that each bidder has some information regarding its cost structure as a function of the type of license that it purchases. Because the profit in the post auction interaction is determined by the respective cost structure in the industry, valuations are interdependent: if A is sold to firm i, i's profit depends on the cost structure of firm j (and hence on $j's$ information) whenever j gets license B. Thus, besides allocative externalities, auctions followed by future interaction, may involve significant informational externalities, leading to the theoretical problems about multi-object auctions discussed in Section 4.2.5[23].

The main lesson is that bidding at such auctions will be driven by subtle considerations, and full efficiency may not even be theoretically achievable. Extra caution must be used at the design stage in order to achieve a desirable outcome.

6 Case Study: The European UMTS License Auctions[24]

Europe has taken the global lead in the issuance of third generation (3G) licenses for mobile telecommunications according to the UMTS/IMT 2000 family of standards[25]. First generation networks offered simple analogue voice telephony; current systems (2G according to the GSM standard) added some data services like fax and e-mail; Besides increased encoding efficiency

[23] See also Goeree (2000) who focuses on signalling in such auctions.

[24] This Section is based and supplants our 2000 CEPR discussion paper "The Euroopean UMTS License Auctions"

[25] Other papers discussing various aspects of the UMTS auctions are: Börgers and Dustmann (2001), van Damme (2000), Grim et.al. (2001), Klemperer (2001).

(up to five times), 3G networks should, in theory, be capable of providing transmission rates up to 2 Megabits per second, and thus the prospect of high-resolution video, multimedia, mobile office, virtual banking, and many other on-line services.

The European licensing activity is summarized in Table 1. Several countries (e.g., Finland, Spain, Norway, Sweden, France) have opted for so called "beauty contests" in which licenses are allocated on the basis of a bureaucratic procedure where several criteria (such as technical expertise, financial viability, network coverage, roll-out speed, etc...) are evaluated. These processes are not transparent, are often prone to intense lobbying and political intervention, and it is difficult to assess whether they fulfill some pre-specified goals.

Other countries (e.g., UK, Holland, Germany, Switzerland, Italy, Austria) decided to allocate licenses via an auction procedure[26]. After observing the auction revenue obtained in places like the UK and Germany, even countries that previously opted for beauty contests changed the rules of the game. For example, Spain considered selling an additional license through auction (the official licensing procedure had been completed long before), and France raised the licensing fee to a staggering Euro 5 Bn per license. But, contrary, to most accounts in the media, revenue maximization was not, and should not, be the main goal of spectrum auctions.

6.1 The Main Goal: Economic Efficiency

Besides merely allocating spectrum, beauty contests or auctions actively shape future market structure in the telecommunications industry. The main goal of most such allocation procedures is economic efficiency, which, correctly interpreted, means the maximization of the (possibly weighted) sum of consumer and producer' surplus. This maximization exercise must necessarily consider several alternative market scenarios. In particular, future firm profits and consumer rents are determined by the number of licensed firms. Of course, a secondary goal is raising revenue for the government[27].

A serious hurdle on the way to economic efficiency[28] is due to the fact

[26]Practically all auctions are preceded by a stage where potential bidders have to qualify in light of technical, financial and other criteria.

[27]The popular media tends to focus on revenue. Moreover, it seems that the UK auction has opened the appetite of several European governments.

[28]Another, more technical difficulty is presented by the fact that, in complex situations fitting well some spectrum auction environments, multi-unit efficient allocation procedures simply do not exist and second-best mechanisms are not yet known (see Jehiel and Moldovanu, 1998).

that consumers do not directly participate at the spectrum auctions or beauty contests. Moreover, an ex-ante measurement of expected consumers' surplus in various market constellations is very difficult. Therefore, consumer surplus does not naturally play a role, unless special provisions are made in a careful design. How should these provisions look like? Since standard oligopoly models predict that in reasonable ranges both consumers' surplus and overall efficiency increase with increased competition among firms, the creation of sufficient market competition becomes a proxy goal that can be successfully implemented by license and capacity allocation schemes. This means that market entry should be actively encouraged as long as it is economically viable. This encouragement must come at the licensing stage since afterwards entry is very hard (due to spectrum scarcity, network effects, regulatory constraints, etc...).

The economic relevant aspects for an efficient 3G licensing started long before a specific allocation procedure is chosen. For example, the amount of spectrum made available for 3G (about 140 MHz) has been decided upon by the International Telecommunication Union (ITU) in a bureaucratic procedure which does not involve pricing of various alternative uses of spectrum. In other words, the created scarcity for 3G spectrum may be artificial. It is obvious that the result of the national allocation procedures would have been quite different if, say, the amount of available spectrum was 300 MHz. Thus, we recommend to introduce some transparent economic reasoning (based on market signals) already at earlier stages in the decision process.

As mentioned in Section 3, the licenses are not well-defined objects and a crucial role is played by their definition (e.g., technical limitations in order to avoid interference, license duration, minimum required network coverage, minimum required roll-out speed, limitations about resale, mandatory roaming agreements, number portability, etc...) If these issues are not properly dealt with, even an "efficient" assignment process may lead to a badly functioning industry ex-post.

6.2 Incumbents and Entrants

Potential new entrants (i.e., firms that do not already operate a GSM network in the respective country) faced two major difficulties: 1) The fixed cost of setting up the infrastructure required for 3G services was very large[29]. In contrast, some of the 2G incumbents' fixed costs were already sunk, since

[29] The estimates are of the order of several billions of Euros for large countries. UMTS operates at higher frequencies, which means that more cells and basis stations are needed than in GSM networks.

they could use significant parts of their already existing facilities[30] (e.g., base station sites[31]). 2) A common prediction is that per-firm industry profit in oligopoly decreases in the number of active firms[32]. Hence, besides expected profits from offering 3G services, incumbents are also driven by entry preemption motives[33] (e.g., the need to avoid further losses relative to the status quo) which translate into increased willingness to pay for licenses and capacity. Moreover, since future 3G operators are usually allowed to offer also 2G services based on the GSM standard, the advent of 3G networks with more active firms is likely to cannibalize some of the incumbents' profits in the 2G area .

For any bidder at a license auction, the "pure" economic value of a license with a fixed capacity is given by the value of expected profits from operating the license. This value increases if the license is endowed with more capacity, and decreases if more firms are licensed.

An entrant's valuation for a license with a fixed capacity is obtained by subtracting from the expected profit (which depends on the expected number of licensed firms) the fixed cost required to build a network.

Besides the need to subtract lower infrastructure costs, an incumbent's valuation for a license with a fixed capacity is obtained by adding to the expected profit (which depends on the expected number of licensed firms) the profit that will be lost relative to status quo if that incumbent does not get a 3G license. Tables 2 and 3 illustrate how a major investment bank estimated license values as a function of the various possible market constellations. While the numbers appear exaggerated from today's vantage viewpoint, it is obvious that market structure considerations and the incumbent/entrant asymmetry played a major role in that bank's estimates.

Assuming that firms are otherwise comparable (in terms of costs, know-how, managerial skill, financial strength, etc...), we obtain that, in any feasible market constellation, incumbents place higher values on licenses than entrants do. Hence, incumbents are willing to bid higher than entrants, and we should expect that all GSM incumbents get licenses if at least one new entrant is licensed. The consequence is that the playing field among incum-

[30] Some incumbents also enjoyed large customer bases and strong brand names.

[31] Finding topographically appropriate sites that conform stringent environmental and building regulations is becoming a major concern.

[32] For the effects of such a specification in license auctions with symmetric firms see Katz and Shapiro (1986), Kamien and Tauman (1986), Rodriguez (1998). Jehiel and Moldovanu (1996a) allow for asymmetry among firms and explicitly consider incumbents and entrants.

[33] These and similar effects are well documented and understood, in particular in the area of innovation - see for example Gilbert and Newberry (1982), Krishna (1993). In the context of spectrum license auctions, see also Jehiel and Moldovanu (2000).

bents and potential new entrants is far from being level, even if the firms are otherwise (e.g., technically, managerially, financially) alike. Entering the market by directly overbidding GSM incumbents seems quite difficult unless new entrants are significantly more efficient and therefore expect higher profits, or incumbents have tighter budget constraints, etc... If potential new entrants perceive this disadvantage[34], they might not bother to bid at all, or they might try to form consortia with incumbents. Both types of behavior are likely to have an adverse effect on competitiveness and revenue.

It is, of course, conceivable that special circumstances lead to an entrant having a higher value than an incumbent. For example, a particular country license may be the "last piece in the puzzle" for a global firm which consequently may be willing to pay more than a small incumbent with only local interests. But such features are hard to predict a-priori, and are subject to constant changes since firms form and break alliances, change business plans, etc... Considerations based on such transitory features do not seem very reliable in practice.

We now briefly describe several main types of rules that were used in the various European countries.

6.3 The Main Rules of Selected European Auctions

6.3.1 The UK Auction

The design revolved around a simultaneous multiple-round ascending auction, augmented by various activity rules that control the speed of the auction and limit to some extent gaming behavior. After each round all bids were revealed to the bidders. The simultaneous approach and the concept of activity rules have been introduced and widely employed by the US Federal Communication Commission[35]. The most important decision concerned the number of auctioned licenses that was finally fixed to be 5, one more than the number of GSM incumbents. Moreover, only new entrants were allowed to bid on license A, which was also endowed with the highest capacity, 2×15 MHz (paired spectrum) + 1×5 MHz (unpaired spectrum). Bidding on licenses B,C,D and E was open to all qualified bidders. License B was endowed with 2×15 MHz , while licenses C, D, E were endowed with $2 \times 10 + 1 \times 5$ MHz each. Hence, both the number of licenses and their capacity endowments were fixed in advance by the regulator.

[34] Klemperer (2000) points out that small perceived advantages ("toeholds") can be transformed in large advantages during the auction due to cautious behavior in order to avoid the "winner's curse".

[35] See for example McMillan (1994), McAffe and McMillan (1996) and Milgrom (1997)

6.3.2 The Dutch Auction

There were 5 licenses and 5 GSM incumbents. Licenses A and B had a capacity of 2×15 MHz, licenses C,D,E had a capacity of 2×10 MHz. The auction was simultaneous and ascending. In each round a bidder could bid on at most one license. Bidders were required to bid at each round in order to remain in the auction. An exception was the possibility of using a "pass" card in the first 30 rounds of the auction. A minimum increment of 10% of the current price was used throughout the auction. The information revealed at each stage consisted of: number of bids on each license, number of highest bids, highest current bidders and their bids. Finally, there was a reserve price of about Euro 50 million for each license, but this price could be reduced after a stage in which no bids were made on that license.

6.3.3 The German and Austrian Auctions

The rather complex design involved two consecutive auctions. The first auction allocated licenses[36] together with so called "duplex" or "paired" spectrum frequencies . The second auction allocated paired spectrum that has not been sold at the first auction, together with additional "unpaired" spectrum. Both auctions were of the "simultaneous multiple-round ascending" type.

The License Auction Bidders did not directly submit bids for licenses. Instead, the auctioned objects are 12 blocks[37] of paired spectrum. Each block consists of 2×5 Mhz.

The crucial design ingredient is as follows: A bidder obtained a license only if he acquired at least two blocks, but a bidder was allowed to acquire (at most) three blocks. As a consequence, both the number of licensed firms and the capacity endowments were endogenous. The number of licensed firms could, in principle, vary between 0 and 6. If all blocks are sold there will be no less than 4 licenses (which equaled the number of GSM incumbents in both Germany and Austria)

Each block had a reserve price of DM 100 Million in Germany and Euro 50 Million in Austria. The design was complemented by various activity rules[38]. Most importantly, at each round a bidder must bid on at least two

[36] Licenses are awarded for a period of 20 years, and no resales are allowed.

[37] Blocks are "abstract", i.e., the exact location of each block in the spectrum will be determined ex-post, to ensure that a bidder gets adjacent blocks.

[38] For example, in each round of the German auction, bids can be increased only by a pre-announced minimum increment which is a multiple of DM 100.000.

blocks (although the blocks were abstract and identical, bids carried name tags). Bidding on only two blocks at round t precluded bidding on three blocks at all rounds $t' > t$.

A block may fail to be sold either because there were no bids for that block above the reserve price, or because the bidder who submitted the highest bid on that particular block ultimately fails to acquire two blocks (and hence fails to be licensed), in which case he is not required to make a payment[39].

The Auction for Additional Capacity The purpose of the second auction was to allocate additional capacity among the bidders that were licensed at the first auction. This means that only those bidders that previously acquired at least two paired blocks of 2×5 MHz were allowed to participate.

Besides unsold paired blocks from the first auction, the second auction was supposed to allocate additional 5 unpaired blocks of 1×5 MHz each[40]. Bidders could acquire any number of unpaired blocks, but were not allowed to acquire more than 1 paired block. Each unpaired block had a reserve price of DM 50 Million in Germany, and Euro 25 Million in Austria.

6.3.4 The Italian Auction

There were a maximum of 5 identical licenses[41] with a capacity of $2 \times 10 + 1 \times 5$ MHz. An interesting rule stipulated that, in case that there are only 5 or less bidders at the auction, the number of licenses can be reduced to be one less than the number of bidders.

In each round a bidder could make one bid and the five highest bids determined the current allocation (hence bids were not named to indicate a particular license). Each winner was supposed to pay his own bid (and not, for example, the highest losing bid). The reserve price was about Euro 2 billion per license.

6.3.5 The Danish Auction

Denmark planned to sell 4 identical licenses, equal to the number of GSM incumbents. The Danish auction was the last one in Europe, and its regulators

[39] Since bidders are, at each round, required to seriously bid on at least two blocks, it is not possible to bid high on a unique bid just in order to make others pay more.

[40] Only 4 of the unpaired blocks are abstract, while the fifth one is isolated, and may be used only under additional constraints. Hence, if 5 firms become licensed at the first auction, at least one of them must get capacity of somewhat reduced quality at the second auction. If the first auction produces 6 licensed bidders, then at least one of them will not be able to acquire any additional capacity at the second auction.

[41] Licenses were awarded for a duration of 15 years.

were probably aware of the problems caused by such a design (after having observed the Dutch outcome). To avoid the problems, the chosen design was a sealed-bid auction: all bidders had to submit sealed bids, and the top 4 bidders were awarded a license. Interestingly, this was a discriminatory auction where each bidder had to pay its own bid, rather than having all bidders pay the highest losing bid.

6.4 Entry Considerations in Practice

An important concern in many (but not all) countries was to alleviate the incumbent-entrant asymmetry and encourage entry[42]. We describe below several main regulatory tools that have been used for this purpose.

6.4.1 The Number of Licenses

An important variable for controlling entry is the number of licenses. The number of new 3G licenses was a hotly debated issue during the UK auction design stage. In order to achieve economic efficiency the eventual UK design actively tried to level the playing field among incumbents and new entrants. Its main feature was reserving the largest license for a new entrant. On that license only entrants were allowed to bid.

An initial plan called for an ascending auction of 4 licenses[43], complemented by a sealed-bid stage to be conducted when only 5 bidders remained active . One of the purposes of the sealed-bid stage was to allow an entrant to overbid an incumbent (which could not react anymore) in the uncertain one-shot sealed-bid procedure (see Klemperer, 2000). After many subsequent deliberations about the "right" number of licenses, the designers fixed it to be 5, one more than the number of incumbents[44].

In contrast to the UK, the Dutch regulatory agency did not recognize that a directed intervention in order to help new entrants is necessary. It organized an auction for 5 licenses, where 5 was also the number of GSM incumbents[45].

The German regulatory agency also did not recognize that a directed

[42] Another related concern (not discussed below) was encouraging participation at the auction. (See Klemperer, 2002 and Binmore-Klemperer, 2002.)

[43] We have vigorously argued against this proposal, for reasons completely analogous to those that guided us in our critique of the German design.

[44] In this transition, the final sealed-bid stage has been abandoned as well.

[45] Of course, the Netherlands is a relatively small country, and it may be argued that 5 firms are sufficient. But then it is not clear to us why that particular auction was considered to be appropriate.

intervention in order to help new entrants is necessary[46] or fair towards established firms. The German design (also used in Austria) allowed both for an endogenous number of licenses and for endogenous capacity endowments, but incumbents could completely preempt entry[47]. An earlier design which called for 5 licenses has been abandoned in favor of the present one, because the flexible design was thought to offer "a fair, undiscriminating, and efficient market solution to the problem of finding the optimal number of licenses". Moreover, general principles of competition policy "require to allow the highest possible number of firms to enter the market".

Related to the number of licenses, the Italian design stipulated that, after the bidders qualify for the auction, the number of licenses can be reduced to ensure that there are more licenses than bidders. Not surprisingly, the number of bidders that were actually willing to bid was equal to the a-priori maximal number of licenses plus one so that no reduction occurred. But one firm very quickly dropped out of the auction (see below for a description of the outcome). That regulatory ingenuity was surpassed by a twist used in a Turkish sequential design where the reserve price for a second license was set to be equal to the selling price of the first license. Consequently, the winner of the first license bid very high, presumably more than expected duopoly profits. Since no second firm could have bid so high for the second license, that license was not sold, leaving the first winner with a monopoly !

Considerations about right number of licenses were not confined to the realm of auction design. Spectrum allocations by other means must also give an adequate answer. Most of the countries which opted for beauty contests adhered to a simple formula that made entry inevitable:

$$\text{Number of 3G Licenses} = \text{Number of GSM Incumbents} + 1$$

In cases where the plan was to auction even more licenses (such as in the Swedish beauty contest), intense pressure was applied by industry to reduce the number of licenses.

6.4.2 Facilitating entry by reducing infrastructure costs

There are several other features, not directly pertaining to the auction rules, that influence the probability of successful entry through auctions. The adop-

[46] REG-TP has offered extensive explanations (more than 100 pages) for the chosen licensing procedure - see the official German document explaining the auction design (AK: BK-1b-98/005-2, page 17) But some of the arguments are based on confusions about the content of various theoretical results

[47] We criticised this feature in a previous working paper called "A Critique of the Planned Rules for the German UMTS/IMT- 2000 License Auction".

tion of all or some of the following rules has the effect of decreasing the infrastructure costs (including financing costs), with a stronger relative effect on entrants. They can play an important role in leveling the field between entrants and incumbents. Italy, for example, wisely adopted all three measures described below.

1. Mandatory roaming requires GSM incumbents to grant, for an appropriate fee, access to their networks while entrants build their own infrastructure. This means that a new entrant can immediately offer 2G services and generate a positive cash flow for the several years it takes to build a new network. The UK design originally included this feature, but it was overturned following a suit brought by an incumbent (DT's subsidiary OneToOne). A "voluntary" agreement between the government and two other incumbents will now guarantee free roaming. In Germany the incumbents complained that a free roaming stipulation infringes on their existing rights, as defined by the terms of their GSM licenses, and the idea was abandoned. The regulatory agency argued that roaming agreements can and will be achieved by bilateral bargaining. Other countries (such as Finland) allowed even the 3G networks to be based on roaming, in the sense that each winner was requested to cover with its network only a relatively small fraction of the population, while relying on roaming for the rest.

2. License fee payment by installments ease the financial constraints on firms. While this benefits all firms, it is particularly important for new entrants whose cash flow is going to be negative in the first years (due to the large infrastructure investment). UK adopted such a plan, but the required interest rate was so high that firms chose not to use the opportunity. In contrast, Germany required full payment 10 days after the auction. As it became clear that the fees are enormous, adverse reactions on the share prices and bond ratings were triggered. These reactions were partly responsible for the timing of the auction's end (see details below). At the moment, several firms are in serious financial difficulties and share prices have plummeted.

3. Mandatory site sharing obliges GSM incumbents to grant access to their antennae and relay installations, so that several firms can use the same facility. The 3G networks will require a denser cell structure than existing 2G networks. Moreover, it is increasingly difficult to obtain authorization for new sites, due to planning and environmental restrictions. Dealing with this issue is thought to constitute a sizable share of the infrastructure costs. Not surprisingly, incumbents have

argued that, due to technical constraints, site sharing is not feasible on a large scale. Germany, for example, did not stipulate site-sharing, and insisted that each winner builds an independent network. But site-sharing is now being considered (given intense pressure from the industry which is now obviously interested to save costs) Interestingly, this implies that the terms of the licenses may be changed ex-post.

6.5 A Stylized Model

We use the following exceedingly simple models in order to make precise several verbal arguments made above. A main feature is that valuations for licenses are endogenous, and depend on market structure. This aspect seemed to be very well understood by firms and analysts. For example, a major investment bank[48], estimated per license values of Euro 14.75 Bn, 15.88 Bn and 17.6 Bn for a German symmetric market with 6, 5, or 4 firms, respectively. As noted in the previous Section, theoretically this means that there are allocative externalities.

6.5.1 A pre-determined number of licenses (UK , Holland, Italy, Switzerland, Denmark, etc..)

The bidders at the auction are the $n \geq 2$ special firms called "incumbents" and $m \geq 2$ firms called "entrants"[49]. A fixed number $k \geq n$ of new 3G licenses are auctioned[50]. We assume that bids can be made in multiples of a minimum increment denoted by ε, and we assume that ε is small enough in relation to the other parameters[51].

Bidders are characterized by values attached to feasible auction outcomes. These **endogenous** values reflect the expected profits in various feasible market constellations. We assume here for simplicity that all incumbents are symmetric, and that all potential entrants are symmetric. Moreover, we assume that values are common knowledge among bidders (a more general and realistic model has been outlined in Section 5 above).

Suppose that $s \leq k$ entrants acquire a new license. We denote then by $\pi(n+s) \geq 0$ the per-firm expected profit in the future mobile telephony

[48] See "UMTS. The countdown has begun" by WestLB Panmure, 2000.

[49] For example, there were 9 entrants bidding in the UK auction.

[50] In all planned or completed UMTS auctions the number of licenses was at least as large as the number of GSM incumbents. For an analysis of the "war of attrition" phenomenon occuring when this assumption is not fulfilled, see Jehiel and Moldovanu (2000).

[51] To be precise, this means that strict inequalities among various valuations and high bids are not reversed if up to three minimum increments are added or subtracted to one side of the inequality.

market for a bidder that acquires a 3G license. This profit is a decreasing function of the total number of licensed firms in the market. We denote by $-\gamma(n+s) \leq 0$ the expected loss (relative to the present status-quo) of a GSM incumbent that does not acquire a 3G license[52]. The positive function γ is also decreasing in its argument. The expected profit of a potential entrant that does not get licensed is zero.

Finally, we denote by c_i and by c_e the fixed costs that must be born by an incumbent and by an entrant, respectively, in order to build a viable 3G network. These costs are deemed to be significant in relation to the above values, and we also make the realistic assumption that $c_e - c_i > \varepsilon$.

Hence, if s entrants acquire a license, an incumbent that acquires a 3G license for a price p gets a payoff of $\pi(n+s) - p - c_i$. An incumbent who does not get a 3G license has a payoff of $-\gamma(n+s)$. An entrant that acquires a 3G license for a price p has a payoff of $\pi(n+s) - p - c_e$. An entrant that does not get a license has a payoff of zero.

Analysis In our present framework, simultaneous ascending auctions have, for each set of parameters, many equilibria, resulting in different allocations and payoffs. Moreover, the equilibrium number of licensed firms may vary with the parameters. Besides various technical details associated with the simultaneous ascending auction (which play no role for our argument[53]), the multiplicity is also caused by the fact that valuations are endogenous and depend on expectations about the final number of licensed firms.

We "ignore" below the reserve prices, i.e., we assume that the relevant equilibrium bids are all above the reserve price. Moreover, we consider below only equilibria where identical objects (licenses or capacity blocks) are sold at the same price (modulo minimum bid increments). In fact, one can construct equilibria where this assumption is not fulfilled, but this symmetry is a reasonable working assumption. Moreover, this feature is considered to be a big advantage of the simultaneous ascending auction.

Claim 9 *Consider any equilibrium where at least one entrant acquires a license (with probability 1). In this equilibrium, each of the incumbents must acquire a license.*

Proof. Consider an equilibrium where $s \geq 1$ new entrants are licensed, and consider a new entrant who payed $p \geq 0$ for its license (call this license

[52] For example, this includes profits that an incumbent expects to loose in the 2G market (relative to the status-quo), or losses felt by the management of a potentially shrinking firm, etc...

[53] For example, we ignore any coordination problems such as "who bids on what blocks".

A). Since the entrant's payoff must be non-negative, we obtain that $\pi(n+s) - p - c_e \geq 0$, which is equivalent to $p \leq \pi(n+s) - c_e$. Assume, by contradiction, that an incumbent does not get a license. In particular, this means that this incumbent bids less than p on license A, and that this incumbent has a payoff of $-\gamma(n+s)$. Consider now a deviation where the incumbent bids $p + \varepsilon$ on the above license. With such a strategy, his payoff becomes $\pi(n+s-1) - (p+\varepsilon) - c_i \geq \pi(n+s-1) - (\pi(n+s) - c_e) - \varepsilon - c_i > c_e - c_i - \varepsilon$ (because $\pi(n+s-1) > \pi(n+s)$) and $c_e - c_i - \varepsilon > 0 \geq -\gamma(n+s)$. Hence, the deviation is profitable, a contradiction to the assumption that we considered an equilibrium. ■

Remark 1: Roughly speaking, the above Claim shows that incumbents have higher valuations than new entrants (recall that valuations are endogenous here). There are three reasons why this is so. First, irrespective of the market structure configuration, the fixed cost c_i of incumbent is higher than that of entrants c_e. Second, incumbents are ready to pay an extra $\gamma(n+s)$ as compared with entrants because of the synergy between 2G and 3G licenses. Third, - since incumbents are already present in the market - the acquisition of a 3G license by an incumbent is less damaging to the per-firm profits than the acquisition by an entrant. This is reflected by the fact that $\pi(n+s-1) - \pi(n+s) > 0$.

Remark 2: In view of the remark above, we implicitly use below the only tie-breaking rule that is consistent with more general formulations (where valuations are continuously distributed and strictly higher valuations lead to strictly higher bids): a new entrant cannot win a license if there is an incumbent who bids at least as high as the entrant on that block.

Claim 10 *Assume that the number of new licenses equals the number of incumbents, i.e., $k = n$, and that $\pi(n+1) - c_e \geq 0$ .The following strategies define an equilibrium: each entrant bids $\pi(n+1) - c_e$ and each incumbent bids $\pi(n+1) - c_e + \varepsilon$. In this equilibrium all incumbents get licensed, there is no additional entry, and revenue is approximately given by $n\pi(n+1)$.*

Proof. If the above strategies are played, entrants get a payoff of zero and incumbents get a payoff of $\pi(n) - \pi(n+1) + c_e - c_i - \varepsilon > 0$. The above strategies form an equilibrium because: 1) Given that all other incumbents bid above $\pi(n+1) - c_e$, an incumbent i has no incentives to bid below that since this means leaving a license to an entrant, yielding a payoff of $-\gamma(n+1) \leq 0$. 2) Given that an entrant expects that all other licenses go to incumbents, the value of a license to an entrant is $\pi(n+1) - c_e$. ■

Claim 11 *Assume that the number of new licenses is higher than the number of incumbents, i.e., $k > n$, and that $\pi(k) - c_e \geq 0$. The following strategies* *define an equilibrium: each entrant bids $\pi(k) - c_e$ and each incumbent bids $\pi(k) - c_e + \varepsilon$. In this equilibrium all incumbents get licensed, $k - n$ entrants also get licensed and revenue is approximately given by $k\pi(k)$.*

Proof. If the above strategies are played, entrants (whether licensed or not !) get a payoff of zero and incumbents get a payoff of $c_e - c_i - \varepsilon > 0$. The above strategies form an equilibrium because: 1) Given that all other bidders bid at least $\pi(k) - c_e$, an incumbent i has no incentives to bid below that since this means leaving a license to an entrant, yielding a payoff of $-\gamma(k+1) \leq 0$. 2) Given that an entrant expects that n out of k licenses go to incumbents, the value of a license to an entrant is $\pi(k) - c_e$. ■

6.5.2 An endogenous number of licenses (Germany, Austria)

The bidders at the auction are the $n = 4$ special firms called "incumbents" and $m \geq 2$ firms called "entrants". Twelve identical blocks are auctioned according to the rules detailed in Section 6.3.3[54].

If s new entrants acquire 3G licenses, we denote by $\pi_q(n + s) \geq 0$ a bidder's value for q blocks, $q = 2, 3$, as a function of the number of licensed firms in the market. We assume that π_q is decreasing in n and increasing in k. The rest of the definitions, notation and assumptions is as above.

Analysis We first prove a Claim that identifies the advantage enjoyed by incumbents.

Claim 12 *Consider any equilibrium where at least one new entrant acquires $q \geq 2$ blocks (and thus it is licensed). In this equilibrium, each of the 4 incumbents acquires at least q blocks (and thus all 4 incumbents must also be licensed).*

Proof. Consider an equilibrium where $n+s$ firms are licensed, including a new entrant who obtains q blocks, $q \geq 2$, by paying b per block. Since the entrant's payoff must be non-negative, we have $\pi_q(n+s) - qb - c_e \geq 0$, which is equivalent to $b \leq \frac{\pi_q(n+s) - c_e}{q}$. Assume, by contradiction, that an incumbent does not get a license. In particular, this means that the incumbent bids less than b on the above blocks, and that this incumbent has a payoff of $-\gamma(n+s) \leq 0$. Consider now a deviation where the incumbent bids $b + \varepsilon$ on the above blocks[55]. With such a strategy, his payoff becomes $\pi_q(n+s-1) -$

[54] We focus here on the main first stage and ignore the additional strategic complexity induced by the presence of the second stage.

[55] In an equilibrium where not all blocks sell for the same price, the proof is modified by letting the incumbent mimic the entrant.

$q(b+\varepsilon) - c_i \geq \pi_q(n+s-1) - \pi_q(n+s) + c_e - c_i > 0 \geq -\gamma(n+s)$. Hence, the deviation is profitable, a contradiction to the assumption that we considered an equilibrium. ■

There are three main outcomes, differing by the number of licensed firms. The next three results determine the conditions on the parameters that are necessary in order to sustain each outcome. The conditions relate the firms' valuations in various market constellations.

Claim 13 *Consider the following strategy profile: each entrant bids on three blocks up to $b_e = \frac{\pi_3(5)-c_e}{3}$ per block; each incumbent bids on three blocks up to $b_i = b_e + \varepsilon$ per block. If $\pi_3(4) - \pi_2(4) \geq \frac{\pi_3(5)-c_e}{3} \geq \frac{\pi_2(5)-c_e}{2}$ then this profile constitutes an equilibrium*[56]*. The licensed firms are the 4 incumbents. The revenue in this equilibrium, approximately $4(\pi_3(5) - c_e)$, is the highest possible among all symmetric equilibria with 4 licensed firms.*

Proof. By the above Claim, if an entrant gets a license in equilibrium, then the 4 incumbents must also be licensed. Hence, the highest value[57] an entrant can ever achieve by being licensed is $\pi_3(5)$. According to the above described bidding strategies, entrants are not licensed, and get a payoff of zero. Bidding below b_e on one or more blocks cannot improve their payoff, while bidding $b > b_e$ on three blocks yields a payoff of $\pi_3(5) - 3b - c_e < \pi_3(5) - 3b_e - c_e = 0$ and bidding $b > b_e$ on two blocks yields a payoff of $\pi_2(5) - 2b - c_e \leq \pi_3(5) - 3b - c_e < \pi_3(5) - 3b_e - c_e = 0$. Hence, the entrants' strategy cannot be improved upon. Consider now an incumbent. By bidding $b_i = b_e + \varepsilon$, he gets three blocks and is licensed. His payoff is given by $\pi_3(4) - 3b_i - c_i = \pi_3(4) - \pi_3(5) + c_e - c_i - 3\varepsilon > 0 \geq -\gamma(4)$. It is clear that bidding higher on some blocks is not optimal. If the incumbent bids lower on two or more blocks, then he looses the license, yielding a payoff of $-\gamma(4) \leq 0$, hence this cannot be optimal. If the incumbent bids lower on one block, then his payoff is given by $\pi_2(4) - 2b_i - c_i \leq \pi_3(4) - 3b_i - c_i$. We conclude that the described strategy is optimal for the incumbent, and that we have described an equilibrium ■

Claim 14 *A necessary condition for the existence of an equilibrium with 6 licensed firms is given by $\pi_3(5) \leq \frac{3\pi_2(6)-c_e}{2}$.*

Proof. By Claim 12, the 6 licensed firms must include the 4 incumbents. In an equilibrium with 6 licensed firms where the block price is b, entrants get

[56] An equilibrium with the same physical outcome (4 licensed incumbents) but different payments exists also if $\pi_3(4) - \pi_2(4) \geq \frac{\pi_2(5)-c_e}{2} \geq \frac{\pi_3(5)-c_e}{3}$.In this equilibrium, entrants bid only on two blocks.

[57] Recall that $\pi_3(5) \geq \pi_2(5)$, and that $\pi_3(5) \geq \pi_3(6) \geq \pi_2(6)$).

a payoff of $\pi_2(6)-2b-c_e$. Since this payoff must be non-negative we obtain $b \leq \frac{\pi_2(6)-c_e}{2}$. An incumbent's payoff is given by $\pi_2(6) - 2b - c_i$. Assume now that an incumbent deviates and bids $b + \varepsilon$ on one block. Then, there will be only five licensed firms, and this incumbent's payoff is given by $\pi_3(5) - 3b - \varepsilon - c_i$. For the outcome with 6 licensed firms to be an equilibrium, it is necessary that $\pi_3(5)-3b-\varepsilon-c_i \leq \pi_2(6)-2b-c_i$. This is equivalent to $\pi_3(5) \leq \pi_2(6)+b$. Because $b \leq \frac{\pi_2(6)-c_e}{2}$, we obtain the necessary condition $\pi_3(5) \leq \frac{3\pi_2(6)-c_e}{2}$. ■

Claim 15 *A necessary condition for the existence of an equilibrium with 5 licensed firms is given by* $\pi_3(4) \leq \frac{3\pi_2(5)-c_e}{2}$.

Proof. The only possible configuration with 5 licenses is one where 2 firms acquire 3 blocks each, and 3 firms acquire 2 blocks each. By Claim 12 we obtain that 2 incumbents acquire 3 blocks each, 2 incumbents acquire 2 blocks each, and a new entrant acquires two blocks. Hence, there are two incumbents that can possibly improve their payoff by bidding on additional capacity. The proof follows exactly as in the previous Proposition. ■

6.6 Comparison between Auctions' Outcomes and Models' Predictions

6.6.1 UK Outcome

There were 13 participating bidders, and 150 rounds of bidding. The results are summarized in Tables 4 and 5. 4 licenses were acquired by the 4 GSM incumbents (with the largest unreserved license going to Vodafone), while the reserved license A was acquired by an entrant, TIW. Total revenue was £22.5 billion. The identical licenses C, D, and E sold for the same price (slightly more than £4 billion), while licenses A and B were more expensive (they were endowed with more capacity). The outcome is the one predicted by Proposition 11, where the number of licenses was higher than the number of incumbents, and where all incumbents get licensed. In particular, Table 5 displays the final bids of all 13 bidders and shows that the average incumbent bid was much higher than the average entrant bid. Higher valuations for incumbents constituted indeed the driving force behind our theoretical results.

6.6.2 Dutch Outcome

There were 6 bidders (5 incumbents, one entrant). The results are summarized in Table 6. The five licenses were acquired by the five GSM incumbents (with the large licenses going to KPN and to Vodafone's subsidiary, Libertel). Total revenue was a relatively low 2.7 billion Euro. These features agree well with the prediction of Proposition 10, where the number of licenses equals the number of incumbents, and where no entrants are licensed. Several interesting things happened during the auction: In the first stages of the auction all bidders used pass-cards, thus bringing the reserve prices (with the exception of one license) to zero ! This considerably prolonged the auction. Also, the only participating new entrant, Versatel, stepped out very early claiming that it was threatened not to drive prices up by an incumbent (BT's subsidiary, Telfort). This disappointing but predicted outcome was the subject of a parliamentary inquiry.

6.6.3 German Outcome

The outcome is summarized in Tables 7 and 8. The German auction was probably the most dramatic one since the government risked a highly concentrated market by explicitly exploiting preemptive motives (probably for the sake of increased revenue). Luckily for the government, the outcome produced both high revenue and two new entries.

There were only 7 bidders (including 4 GSM incumbents), after 6 other qualified bidders ultimately withdrew from the auction. The auction's first stage lasted for 3 weeks and 173 rounds of bidding, and resulted in 6 licenses being awarded. The licensed firms were the 4 incumbents and two new entrants (one of them already operating as service provider). Each licensed firm acquired 2 blocks of paired spectrum at the main license auction (recall the complex design described above), and each license cost approximately Euro 8.4 Bn (or Euro 4.2 Bn per block). The most interesting thing occurred after one of the potential entrants, Debitel, left the auction after 125 rounds and after the price level reached Euro 2.5 Bn per block. Since 6 firms were left bidding for a maximum of 6 licenses, the auction could have stopped immediately. Instead, the remaining firms (and in particular the two large incumbents) continued bidding in order to acquire more capacity. But no other firm was willing to quit, and, after intense pressure from stock markets and bond rating agencies[58], bidding for more capacity stopped in round 173. Compared to round 125, there was **no change** in the physical allocation, but firms where, collectively, **Euro 20 Bn poorer**!

A design that allows for a flexible number of licenses and a flexible capacity endowment for these licenses completely endogenizes the bidders' valuations and opens the door to complex gaming behavior during an ascending

[58] Most bond ratings for the involved firms were subsequently downgraded from AA to A.

auction. Besides the allocative externalities, the design induced multi-unit demand and demand-reduction aspects (recall the associated problems displayed in Section 4.2)

Ewerhart and Moldovanu (2001) explain the bizarre outcome via equilibrium analysis in an ascending format with incomplete information: The specific capacity limitation rules implied that in any possible auction outcome which includes entry (with 5 or 6 licensed firms) there is at least one new firm (this must be an entrant by Claim ?) that has acquired exactly the minimum mandated two blocks. If this firm looses one block, then it looses the entire license. Thus, besides getting "pure" economic value by acquiring one block of capacity in excess of the minimum two blocks, an incumbent gets substantial extra value because it can deny an entire license to a new entrant, thus avoiding a foreseeable decrease in expected profits caused by additional entry. In this sense there were strong complementarities among blocks, and this created an exposure problem similar to the one discussed in Section 4.2.2. Ewerhart and Moldovanu also show that, with positive probability, firms may ex-post regret the equilibrium outcome. This surely happened in reality since pre-emption failed and the final outcome could have been achieved at much lower cost.

Why pre-emption ultimately failed ? Besides the growing pressure from stock-markets and bond-rating agencies during the auction, note that there were only two financially strong incumbents. Since prices were already high when Debitel stepped out, at least one entry looked plausible. As one entry was likely to occur, the value of avoiding a second entry was somewhat reduced (even though the two big incumbents were apparently ready to pay a lot to have only five licensees), and strategic demand-reduction finally occurred.

Another intriguing explanation for the level of prices arises by noting that DT is still majority owned by the German government. Hence, by driving up prices, DT clearly served the interest its major shareholder who happened to be the auctioneer (while the price it paid itself can be partly seen as a transfer from one government pocket to another)[59].

In the second stage 5 firms (3 incumbents and 2 entrants) each acquired an additional block of unpaired spectrum. There was no serious bidding in which firms tried to acquire more capacity - note that the preemptive motive was greatly reduced in that stage since the number of licenses was already determined. It seems that the enormous price paid at the first stage did not allow further flexibility (in particular, the smallest incumbent Viag Interkom

[59] Several winning firms expressed their anger about that. A lawsuit was brought by one of the small incumbents, but it was not further pursued.

was so budget constrained that it could not afford serious bidding at all).

Finally, it is interesting to note that some firms are now lobbying the government: they ask to operate via a shared network (in blatant disagreement to the licenses' terms which state that a firm which does not roll-out an independent network must return the license and the attached spectrum capacity). Klaus-Dieter Scheurle, head of Reg-TP at the time of the auction thinks now that 6 networks are an "illusion".

6.6.4 Austrian Outcome

In Austria there were exactly 6 bidders (4 of them GSM incumbents) for a maximum of 6 licenses. Hence, in principle, the license auction could have ended immediately, at the reserve price (Euro 100 mil. per license). But the license auction continued for another 16 rounds, before stopping with...6 licensed firms, each paying Euro 120 mil. per license (see Table 9). Hence, about Euro 120 mil. have been again spent for "nothing" while firms tried to buy more capacity and reduce the number of licenses. But, after observing the German outcome, firms probably understood the inherent danger of exposure, and quickly reduced demand. Some commentators imply that the rounds of bidding were just "pro-forma" in order not to give the impression that some collusive agreement among firms was in place.

6.6.5 Italian Outcome

There were 6 bidders, 4 incumbents and 2 new entrants. Hence, according to the rules, the number of licenses was not reduced and remained fixed at 5, and at least was one new entry was inevitable. The auction ended after 11 rounds, after Blu, the smallest and weakest incumbent, dropped out. The remaining 5 firms paid about Euro 2.4 billion per license (see Table 10). Apparently, Blu gave up following serious conflicts about financing between the Italian shareholders and the main foreign backer, BT. The government was furious about the early end of the auction, and accused Blu of and other firms of manipulations[60]. Threats to cancel the auction while forfeiting the deposits (which were about as high as the final prices) were aired. Finally, the auction's outcome has been authorized. It is possible that, besides Blu's management and organization problems, the relatively generous stipulations made for entrants (see Section 6.4.2) contributed to the auction's outcome.

[60] The idea was that Blu has been possibly "asked" to take part in the auction by other firms, thus keeping the number of licenses at 5.

6.6.6 Danish Outcome

The sealed-bid procedure introduced lots of uncertainty in the auction since firms could not react anymore to a bid placed by competitors. In particular, one entrant bid more than an incumbent - besides the peculiar case of Blu in Italy (see above), this is the only instance when an incumbent was not successful.

6.7 Collusion

All above considerations were based on a behavioral model which assumes that bidders do not collude. Of course explicit collusion during the auction is forbidden by the auction rules in all countries, and usually severe steps are taken to ensure that bidders cannot directly communicate during the auction. But "tacit collusion" remains a major issue. We briefly discuss here several issues that also relate to the incumbent -entrant asymmetry. For other themes related to collusion see also Klemperer (2000)

Jehiel and Moldovanu (2000) argue that the simultaneous ascending auction (through its dynamic, iterative structure) is well suited for incumbents who wish to coordinate in order to prevent entry[61] (without the need of external monetary transfers). Well designed activity rules can partly alleviate this problem, but cannot completely solve it.

To illustrate how coordination through signaling of intentions (which is legitimate given a design that makes it possible) might work, it is instructive to recall the result of the October 1999 German auction of extra capacity for the GSM-1800 standard. The auction covered 10 blocks of paired spectrum. Nine blocks were identical, each consisting of 2×1 MHz, while the tenth block consisted of 2×1.4 MHz. Reasonably, only the 4 GSM incumbents were allowed to bid. Besides a clear need for extra capacity in congested areas, it is possible that the large players (DT's subsidiary T-Mobil, and Vodafone's subsidiary Mannesmann) were driven by a preemptive motive. The auction was conducted in a simultaneous ascending format and the rules did not contain any limitation about the capacity that can be acquired by any one firm. The auction proceeded as follows: After the first round, the high bidder on all 10 blocks was Mannesmann, which offered DM 36.360.000 for each of blocks 1-5, DM 40.000.000 for each of the blocks 6-9 (which, recall, are identical to blocks 1-5), and DM 56.000.000 for the larger block 10. In the second round, T-Mobil bid[62] DM 40.010.000 on blocks 1-5, and the auction

[61] They also discuss the possibility of explicit collusion which requires external monetary transfers. For this, see also Caillaud and Jehiel (1998).

[62] Minimum increments had to be 10% of the last high bid.

closed. Hence, each of the two larger firms got 5 blocks , at a price of DM 20.000.000 per MHz. Here is what one of T-Mobil's managers said: "No, there were no agreements with Mannesmann. But Mannesmann's first bid was a clear offer. Given Game Theory, it was expected that they show what they want most." (*Frankfurter Allgemeine Zeitung*, October 29, 1999, p.13).

Jehiel and Moldovanu (2000) also analyze how the possibility of tacit collusion (requiring no explicit agreement) is affected by other features of the auction format, most importantly the relation between the number of incumbents and the number of licenses. An insight derived there is that, from the point of view of incumbents, sustaining the best collusive outcome as a Nash equilibrium in the auction is more difficult (and may fail) if there is no focal, symmetric method which allows the incumbents to share the preemption cost. In such a case there might be free-riding among incumbents, since each one of them prefers to let other incumbents pay a higher share of the cost [63]. In the German 3G design there was an additional, countervailing, effect since buying more capacity (which could preempt entry) had also a pure economic value. Towards the end of the auction there was clear signaling activity among the two large incumbents who try to sort out whether to continue bidding in order to reduce the number of entrants. Mannesmann made several bids where the smallest free digit (i.e., taking into account the rules that allowed only bids in multiples of DM 100000) was 6, suggesting that it was finally ready to accept an outcome with 6 firms. Initially, DT responded with bids ending in 5, suggesting that it was willing to bid even higher in order to reduce the number of licenses to 5. Only after further price increases and increased nervousness in the stock markets bidding stopped.

6.8 Concluding Comments

Besides allocating spectrum, the UMTS license auctions shaped future market structure in irreversible ways. A successful design must level the playing field among incumbents and potential entrants. The asymmetry among incumbents and entrants is a constant feature of most license auctions, while many other features (such as particular aggregation interests or particular alliances across countries) are of a more transitory nature. Designs that encourage entry will result in increased efficiency, but they will also generate more revenue since more bidders will be attracted by the auction if they perceive real chances of winning.

Given the increased global nature of the telecommunication industry, it

[63] For example, in Germany, there was a method permitting a symmetric allocation of blocks while avoiding entry. But incumbents were not symmetric.

may be worthwhile thinking about the advantages and disadvantages of some kind of "European super-auction" that allows the aggregation of continent (or EU) wide licenses besides the national ones. Even if spectrum allocations remain national affairs for the foreseeable future, some harmonization measures may be required. At the moment, many firms have complained that beauty contests always favor national incumbents, while those incumbents (which often got licenses almost for free in their own country) can freely compete with deep pockets in other countries' auctions.

Finally, additional thought should be given to the issue of post-auction capacity resale. It is not very likely that allowing resale will solve all problems discussed above, no matter how the allocation procedure was achieved (see Jehiel and Moldovanu, 1999). But there is no reason to forbid some regulated form of secondary market in order to better adjust to a rapidly changing environment during the many years when licenses are valid.

7 Summary of Main Lessons

We conclude this paper with a brief summary:

1. Each market process creates specific strategic incentives for the participants and leads to specific distortions once these participants have market power. The performance of various market rules under explicit consideration of strategic aspects stemming from the exercise of market power is the main subject of the large body of theoretical and practical work known under the name of "Auctions and Mechanism Design" .

2. In auctions, participants submit "bids" representing their demand or supply functions. Then accepted trades (that must equate demand and supply) and transaction prices are calculated via some explicit (possibly dynamic) aggregation procedure. Thus, auctions directly implement the ideas implicit in the Walrasian analysis, and the "Walrasian auctioneer" looses its "deus ex machina" status.

3. Auctions can be used to achieve a variety of goals (e.g., efficiency revenue maximization, value discovery, transparency, etc...) A first rule for practical auction design is to clearly identify the auction's main goal (or combination of goals). In complex environments, some trade-offs with respect to other goals are unavoidable.

4. Besides the auction's rules, the most important determinants of theoretical auction performance are related to the economic features of

demand and supply in the underlying situation. How the traded goods and the feasible bids are structured play a main role in determining whether the auction procedure can accurately represent the agents' preferences. Only by choosing an auction format that takes into account the strategic issues arising during the translation of preferences into bids will it be possible to attain the auction's goals.

5. Multi-object auctions raise a large number of difficulties. Even when externalities (allocative of informational) are absent, multi-unit demand, heterogeneity and complementarities induce complex demand functions, which are difficult to map in reasonably simple auction formats. Such formats necessarily restrict bidders in some aspects, creating complex strategic effects that affect the auction's performance. Moreover, several fundamental theoretical problems (such as finding the revenue-maximizing multi-object auction, or the constrained efficient multi-object auction when informational externalities are present) are still open.

6. If the auction's allocation influences the equilibrium of an ensuing interaction, bidders will take this effect into account at the bidding stage. Thus, the channel of influence between auction and future interaction goes both ways: the auction's outcome influences the future interaction through the resulting allocation of assets, and the future interaction influences the auction's outcome through the participants' expectations about their payoffs in various future constellations. In such complex environments it is necessary to base practical auction engineering on a sound theoretical foundation that combines the insights of Auction Theory (in particular auctions with allocative and informational externalities) with the traditional concerns of Industrial Organization.

7. The results of the European UMTS license auctions present a lot of variance. Some of this variance can be explained by country-specific differences in the mobile telephony market (including the pre-existing incumbents' situation in the GSM market) and by timing (e.g., the relations to the sharp fall in the prices of technology stocks in the relevant period) . But, in a number of instances, the auction design influenced the outcome to a large extent. Besides the questions arising from the need to carefully match the auction design to the particular IO situation in each application, we see three interesting questions where more (economic) thinking is needed : a) What would be the effect of EU-wide licenses ? b) How to organize and regulate a secondary market for spectrum ? c) Is it possible to base the deliberations about

how much spectrum is allocated for each application predominantly on economic (rather than technical) aspects ? In particular, does it make sense to allocate spectrum without mandating a specific use, and let the market "work"?

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9 Tables

Country	Population (millions)	Spectrum (MHz)	Mechanism	Licenses	New Entrants
Austria	7.9	145	auction	6	2
Belgium	10.1	140	auction	3	0
Denmark	5.2	155	auction	4	1
Finland	5.3	140	beauty contest	4	1
France	58.4	140	beauty contest	?	?
Germany	82.0	145	auction	6	2
Greece	10.5	140	auction	3	0
Ireland	3.6	155	beauty contest	?	?
Italy	57.4	125	auction	5	1
Netherlands	15.3	145	auction	5	0
Norway	4.4	140	beauty contest	4	1
Portugal	9.9	140	beauty contest	4	1
Spain	39.2	140	beauty contest	4	1
Sweden	8.8	140	beauty contest	4	1
Switzerland	7.0	140	auction	4	1
UK	58.7	140	auction	5	1

Table 1: European 3G license allocation

Market Structure	**Firm Type**	**Valuation**[64] **(£ Bn.)**
5 firms, 1 new entrant	large incumbent with 3G license	32.1
5 firms, 1 new entrant	small incumbent with 3G license	22.2
6 firms, 2 new entrants	large incumbent without 3G license	12.5
6 firms, 2 new entrants	small incumbent without 3G license	8.1
5 firms, 1 new entrant	new entrant with 3G license	6.4

Table 2: UK valuations

Market Structure	**Firm Type**	**Valuation**[65] **(Eu Bn.)**
4 firms, 0 new entrants	large incumbent with 3G license	88.4
5 firms, 1 new entrant	large incumbent with 3G license	78.3
6 firms, 2 new entrants	large incumbent with 3G license	47.8
5 firms, 1 new entrant	large incumbent without 3G license	36.3
5 firms, 1 new entrant	new entrant with 3G license	14.5

Table 3: German valuations

[64] Dicounted expected profit minus capital expenditure (excludes license price). Source: Deutsche Bank Equity Research

[65] Dicounted expected profit minus capital expenditure (excludes license price). Source: Deutsche Bank Equity Research

UK Licence	**Bandwidth MHz**	**Holder**	**Bid (£ Bn.)**	**Bid (Eu Bn.)**	**Price/MHz (Eu Mil.)**	**Price/Pop (Eu)**
A	$2 \times 15 + 1{\times}5$	TIW	4.38	7.23	206	126
B	2×15	Vodafone*	5.96	9.84	328	172
C	$2 \times 10 + 1 \times 5$	BT*	4.03	6.65	266	116
D	$2 \times 10 + 1 \times 5$	One2One*	4.00	6.60	264	115
E	$2 \times 10 + 1 \times 5$	Orange*	4.10	6.76	274	118
Total	**140**		**22.47**	**37.08**		
Average	**28**		**4.49**	**7.41**	**264**	**129.4**

Table 4: Outcome, UK Auction
(* indicates GSM incumbents)

UK Bidders	Backers	Last Bid (£ Bn.)	Last Bid (Eu Bn.)
Vodafone *	Vodafone	5.96	9.84
BT3G *	BT	4.03	6.65
One2One *	DT	4.00	6.60
Orange *	Orange	4.10	6.76
Average Incumbent		**4.52**	**7.46**
TIW *	TIW	4.38	7.23
NTL	NTL, FT	3.97	6.55
SpectrumCo	Sonera	2.10	3.47
Epsilon Tele.com	Nomura	2.07	3.42
3GUK	Eircom	2.00	3.30
Crescent Wireless	Global Crossing	1.82	3.00
Global Wireless	One.Tel	2.18	3.60
Telefonica UK	Telefonica	3.67	6.05
WorldCom Wireless	MCI Worldcom	3.17	5.24
Average Entrant		**2.82**	**4.65**
Average		**3.34**	**5.51**

Table 5: Final Bids, UK Auction
(* indicates a winning bidder)

Dutch Licence	**Bandwidth MHz**	**Holder**	**Bid (Eu Bn.)**	**Price/MHz (Eu Mil.)**	**Price/Pop (Eu)**
A	2×15	Libertel (Vodafone)*	0.713	23.76	44.84
B	2×15	KPN*	0.711	23.7	44.71
C	2×10	Dutchtone (FT)*	0.435	21.75	27.35
D	2×10	Telfort (BT)*	0.430	21.5	27.04
E	2×10	3G Blue (DT, etc...)*	0.394	19.7	24.77
Total	**120**		**2.683**		
Average	**24**		**0.536**	**22.35**	**33.74**

Table 6: Outcome, Dutch Auction
(* indicates GSM incumbents)

German Bidders	Backers
T- Mobil*	Deutsche Telekom
Mannesmann*	Vodafone
E-Plus*	KPN, Hutchison
VIAG Interkom*	VIAG, BT
Mobilcom Multimedia	Mobilcom, France Telecom
Group 3G	Telefonica, Sonera
Debitel	Swisscom

Table 7: Bidders in the German Auction
(* indicates GSM incumbents;)

Germany Licence	Bandwith MHz	Holder	Bid I. Stage (Eu Bn.)	Bid II. Stage (Eu Bn.)	Price/M (Eu Mil
1	$2 \times 10 + 1 \times 5$	Mannesmann*	8.42	0.061	339
2	$2 \times 10 + 1 \times 5$	T-Mobil*	8.47	0.062	341
3	$2 \times 10 + 1 \times 5\#$	E-Plus*	8.39	0.037	337
4	2×10	Viag Interkom*	8.44		422
5	$2 \times 10 + 1 \times 5$	Mobilcom	8.36	0.061	336
6	$2 \times 10 + 1 \times 5$	Group 3G	8.40	0.062	338
Total	**145**		**50.51**	**0.286**	
Average	**20**		**8.42**	**0.057**	**352**

Table 8: Outcome, German Auction
(Debitel left the first stage with a last bid of Euro 5 billion)
(* indicates GSM incumbents)
(# indicates unpaired block of lesser quality)

Austria Licence	Bandwith MHz	Holder	Bid I. Stage (Eu Mil.)	Bid II. Stage (Eu. Mil)	Pri (Eu
1	2×10	3G Mobile	117		5.8
2	2×10	Connect*(Orange, etc...)	120		6
3	$2 \times 10 + 1 \times 5$	Hutchison 3G	114	25	5.5
4	$2 \times 10 + 2 \times 5$	max.mobil*(DT)	119	51	5.6
5	2×10	Mannesmann 3G#	113		5.6
6	$2 \times 10 + 2 \times 5$	Mobilkom* (TI)	121	51	5.7
Total	**145**		**704**	**127**	
Average	**24.16**		**117.3**	**21.16**	**5.7**

Table 9: Outcome, Austrian Auction
(* indicates GSM incumbents)
(# Mannesmann was a already a service provider, but without own network)

Italy Licence	Bandwith MHz	Holder	Bid (Eu Bn.)	Price/Mhz (Eu Mil.)	Price/Pop (Eu)
A	$2 \times 10 + 1 \times 5$	Omnitel*(Vodafone)	2.448	97.92	42.64
B	$2 \times 10 + 1 \times 5$	Tim*(TI)	2.417	96.68	42.10
C	$2 \times 10 + 1 \times 5$	Wind*(FT)	2.428	97.12	42.29
D	$2 \times 10 + 1 \times 5$	Andala	2.428	97.12	42.29
E	$2 \times 10 + 1 \times 5$	Ipse	2.443	97.72	42.56
Total	**125**		**12.164**		
Average	**25**		**2.432**	**97.31**	**42.37**

Table 10: Outcome, Italian Auction
(* indicates GSM incumbents)
(Blu* left the auction with a last bid of Euro 2.319 Bn.)