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The Case of the German DCS-1800 Auction

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By *Klaus Abbink*, *Bernd Irlenbusch*, *Bettina Rockenbach*, *Abdolkarim Sadrieh*, and *Reinhard Selten*[*]

Contents

I. Introduction

Radio frequencies are a scarce resource. While sales numbers of mobile handsets have rocketed in the last few years, the spectrum to carry the traffic

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[*] The experimental work presented in this paper was part of a concluded consulting project for a telecommunications operator that participated in the German DCS-1800 auction. Previous to and during the auction, the work was exclusively known to the advised bidder and no information was exchanged with other parties. None of the authors is or was affiliated to the bidder. As usual, all views expressed and all errors made are our own. We thank the experts and the executives of the advised bidder for providing valuable assistance in designing the experiment. We also gratefully acknowledge the financial and organisational support that was provided. We further thank *Friedel Bolle*, three anonymous referees, and the seminar participants of the CESifo conference on Spectrum Auctions, November 2001 in Munich, for helpful comments and suggestions.

naturally cannot grow at the same pace. Future data intensive technologies will put an additional strain on the limited resource. Thus, the only way out is to use the existing radio spectrum most efficiently. To this aim, auctioning spectrum off has become a common device. The idea is that those operators who can make the best economic use of the frequencies will value them highest and win the auction, thus the spectrum is allocated in a way maximising economic efficiency.

However, in order to allocate the spectrum to the most efficient operator in the best-suited way, the auction must be carefully designed, and the bidders need to be well prepared to be able to make best use of their available budget. Designs for spectrum auctions are often relatively complex. The money at stake is huge, which makes the implementation of a suitable bidding strategy a challenge for every bidder involved in an auction. During their preparation for a spectrum auction, participants often seek advice from academic scholars, in particular game theorists.[1] This paper reports a case study from the Digital Cellular System on the 1800 MHz Frequency Band (DCS1800) auction held in September 1999 in Germany. In this auction, 2×10.4 MHz of spectrum in the 1800 MHz range were put up for sale among the four operators active in the German GSM market. The spectrum was earmarked as extension of the spectrum endowment for the licensed mobile telecommunications operators. New entrants were not admissible to the auction, since the spectrum was not considered as sufficient to set up a new network.

One of the bidders in the auction approached us to provide strategic advice in the preparation for the event. We suggested a behavioural approach rather than a merely game theoretical one. This approach is based on empirical evidence gathered in controlled experiments with student subjects as well as on the managers' own experience in training sessions.[2] The lessons learnt from the experiments are complemented by theoretical strategic considerations, all of it to be integrated into the design of a bidding strategy.[3] The present paper describes the steps on the way towards the implementation of a bidding strategy.

II. Background

At the time the auction was prepared, Germany had four nationwide GSM networks with a very asymmetric distribution of market shares. The two companies, which started operation already in the early 1990s, were T-Mobil (today T-Mobile Deutschland) and Mannesmann Mobilfunk (MMO, today Vodafone).

[1] For an earlier case study see *Salant* (1997).

[2] Other experiments motivated by spectrum auctions are reported in *Plott* (1997), *Bolle* and *Breitmoser* (2001a), *Abbink*, *Irlenbusch*, *Pezanis-Christou*, *Rockenbach*, *Sadrieh*, and *Selten* (2001), and *Plott* and *Salmon* (2001). The issue of multi-unit demand auctions has been experimentally analysed by *Kagel* and *Levin* (2001).

[3] Our theoretical considerations were restricted to the discussion of the strategic implications of various types of bidding behaviour, especially of those that emerged in our experiments. We did not analyse game equilibria. Other authors have taken theoretically more sophisticated approaches, investigating the equilibria of numerous specifications of multi-unit auctions, for example see *Menezes* (1996), *Ausubel* and *Schwarz* (1999), *Grimm*, *Riedel*, and *Wolfstetter* (2001), *Bolle* and *Breitmoser* (2001b), *Brusco* and *Lupomo* (2001).

They were of similar size with about 7 million subscribers each at that time. Both operated only in the 900 MHz (D) frequency band. The two other GSM network operators being active in the 1800 MHz (E) band started later (1996 and 1998). E-plus had a subscriber basis of 3.5 million customers, while Viag Interkom (after rebranding today known as mmO2) had only 300,000 subscribers by that time. The market was booming with customer growth rates of annual 50-100%.

The spectrum endowment between the two groups of operators was distributed exactly opposite to the size of the subscriber basis. Both D band operators were endowed with 2×12.5 MHz each, while each of the E band networks could use 2×22.5 MHz allocated to them with their original licence.[4] Increasing traffic and rising subscriber numbers made capacity constraints a concern for the D band operators.

The capacity of a mobile telecommunication network is not proportionally related to its spectrum endowment. The spectrum only defines the capacity within a given cell. Thus, capacity of the network can in principle be increased also by installing smaller cells. Capacity and cell size are not perfect substitutes. On the one hand, a small cell network still has capacity limitations if traffic is heavily concentrated within single cells. On the other hand, smaller cells allow enhanced coverage within buildings, which is a quality advantage independent from the capacity effect. However, in general there is still ample room for manoeuvre to take the one or the other action to increase the network's capacity.

Though urgent need for capacity extension on the side of the E band operators seemed implausible, the government decided to admit all four operators for participation in the auction. Some managers of the E network operators argued that since the new spectrum was in the E band, it should be awarded to them because of the technical homogeneity. In fact, integrating the E band frequencies in an existing D band network requires substantial investment. Furthermore, only customers having a dual band handset would benefit from the additional capacity. By that time, dual band handsets were not yet ubiquitous, though it could be expected that this would not take very long. All operators pursued a policy to subsidise the sales of handsets generously conditioned on two-year contract commitments. As a result, few customers used handsets older than two years, and most new handsets were dual band devices.

The government decided to award the spectrum to the winners in the auction for the entire term of their respective licences. With respect to the sales prices, it did not account for the differences in the term of the licences between the operators. All licences had originally been granted for 20 years, but since the E band operators had started later, they had more years left. The D band operators' licences expire in 2009, while the one of E-plus terminates in 2012, and Viag Interkom can operate even until 2016 on their current licence.

[4] However, because of the different frequency range, the per MHz capacity of spectrum in the two bands is not exactly comparable.

III. The Auction Design

The auction design was developed with the advice of the *Wissenschaftliches Institut für Kommunikationsforschung* (wik). It is a variant of the simultaneous ascending auction used in the US in earlier FCC auctions. In this type of auction, all packages of spectrum are sold in the same auction. The bids are increased in bidding rounds, where the bidders can bid on all lots simultaneously. The auction ends when no new bids are submitted.[5]

The detailed rules were communicated to the bidders relatively early. The *Regulierungsbehörde für Post und Telekommunikation* (RegTP) decided to fragment the 2×10.4 MHz into nine blocks of 2×1 MHz and one slightly larger block of 2×1.4 MHz. These lots were abstract; i.e. a lot in the auction was not attributed to a particular frequency in the band. Rather, the spectrum was allocated to the auction winners after the auction in a technically efficient manner.

The lots 1-9 were blocks of 2×1 MHz; lot 10 was the 2×1.4 MHz block. In the first round, all bidders could place bids on any lots, with no limitations on the number of lots to bid for. The minimum bid was DM 1m[6] for each of the lots 1-9, and DM 1.4m for the larger block. There were no upper limits for a particular round.[7] A bidder submitted all his bids simultaneously. After all first round bids were collected the highest bidders were made (preliminary) holders of the respective lots. If more than one bidder had submitted the highest bid, the one that had been submitted first determined the holder.

In the following round, all bidders could overbid the current prices, where the minimal increment was set by the auctioneer. The increment was 10% at the outset of the auction, but it could be decreased to 5% or 2% at the discretion of the auctioneer. All following rounds were held in the same manner.

In all rounds following the first, the number of lots a bidder was eligible to bid for was limited by its active bids. The number of active bids is defined as the number of lots the bidder holds, plus the number of bids placed on other lots. The number of active bids could not be higher than it had been in the round before. Thus, if a bidder once decided not to go for all ten lots anymore, the surrendered bidding rights could not be re-gained later on.

After each round the following feedback was given: For each lot, it was made known who was the current holder of the lot, and the current price. The single bids were not made public. The number of active bids of other bidders was not announced either.

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[5] For discussions of the FCC auctions and its European successors see *McMillan* (1994), *Cramton* (1995), *McAfee*, and *McMillan* (1996), *Ausubel*, *Cramton*, *McAfee*, and *McMillan* (1997), *Keuter* and *Nett* (1997), *van Damme* (1999, 2002), *Jehiel* and *Moldovanu* (2000), and *Klemperer* (2002).

[6] One DM is equivalent to € 0.51.

[7] There was an additional rule that whenever the price of a lot would be DM 2bn or more, the lot was immediately sold to the holder, and the offer could not be overbid. The motive behind this rule remains unclear.

The auction ended either when no new bids were submitted, or when the auctioneer announced the end. The end of the auction could be announced at the auctioneer's discretion before any round following round 20 with a two round lag (i.e. the auction ended two rounds after the announcement.). The holders after the last round were the winners of the items.

IV. The Bidders' Goals, Scenarios, and the Payoff Function

At the heart of the behavioural approach are the experiments with students and company executives. For these, it is essential to reflect the goals of the involved bidders appropriately. All bidders face a task with great uncertainty, because both the bidding behaviour and the goals of the other bidders are unknown. Further, even evaluating the value of spectrum for the own company is a non-trivial task, because the value is affected by very different considerations. Information needed to assess the spectrum value is often held in different departments of the company, as engineering, financial, and marketing expertise is needed to develop the company's goals in the auction.

Before setting up the experimental design, we held extensive interviews with senior managers from all over the company. Our interview partners included engineers, marketing managers, financial managers, strategic business planners and others. All interviews with the experts were held separately in order to avoid *groupthink* effects, the phenomenon that group members (esp. members of an organisation) tend to harmonise their originally diverse beliefs within their group (for a review and further literature see Esser 1998). A within group aggregation of the information that could have lead to *groupthink* had to be avoided. This ensured that the full range of information on spectrum valuation that was available within the organisation was actually conveyed to us. We collected the information bit by bit and used simple rules to aggregate it. Specifically, we examined the distributions of valuations and the distributions of probabilities that were reported for all possible states. We dropped all states that were only mentioned in a single interview. For all other states, we derived estimates from the distributions. Finally, using the analysis of the interviews, we could identify several factors that seemed essential for the spectrum's valuation of the four GSM operators.

The distributions of valuations that emerged from the interviews were used to define the bidders' valuation ranges used in the experiments. Furthermore, certain goals that were frequently mentioned in the interviews were also implemented in the experimental payoffs. Hence, the experimental payoff scheme was designed in a way to induce monetary incentives that were strictly correlated to the bidders' goals as derived from the interviews. Pursuing the defined goals was perfectly incentive compatible for the subjects in the experiments, because they received real monetary payoffs that depended on the extent to which they achieved the aims of the bidders they represented.

The payoff tables we used in the experiments are depicted in the appendix. Notice that each bidder can be in one of two possible *scenarios*: *expansive* or *conservative*. These scenarios reflect the uncertainty present before the auction. They differ not only with respect to the budget – expansive bidders would be expected to have a far higher budget than conservative ones –, but also with respect to the goals they pursue in the auction.

Expansive operators aim at purchasing all or at least most of the spectrum. Their valuation for the spectrum is superadditive, i.e. the additional value of an additional MHz increases with the quantity of spectrum. This can be the case e.g. if an operator plans to introduce a radically new technology for which a large frequency band is needed, but which cannot be covered within the original spectrum the operator already has.

The valuation function of conservative bidders, on the other hand, is subadditive, i.e. the marginal value of spectrum decreases. This is the case if a bidder needs the spectrum to secure that the existing or expected services could be offered in high quality. For this goal, it is not necessary to purchase all spectrum, extending the frequency band by about 2×5 MHz would be sufficient to satisfy this goal. Purchases exceeding 2×5 MHz would still induce positive marginal value, but far less than the first 2×5 MHz.

The payoff tables also include additional goals. The bidders A and B, who represent the D band operators, need a minimum requirement of 2×2.4 MHz in order to integrate the new frequencies into their networks. Thus, the value of less than 2×2.4 MHz is zero.[8] Further, bidders A and B are concerned about their frequency endowment relative to their main competitor. The possibility of rivalistic behaviour (a positive value of increasing the competitors' prices without buying spectrum) is reflected in the bonus that bidders C and D receive.

With four bidders and two scenarios for each bidder we obtain $2^4 = 16$ combinations of scenarios. Realising all of them in the experiments is generally not possible within the given resources, and it would have convoluted the analysis. Therefore, the most interesting scenarios had to be selected. We decided to omit combinations with both E operators in the expansive scenario, which appeared especially unlikely. This left eight experimental conditions to be implemented.

In most theory-driven auction experiments, the items are given a "value" and the payoff the subject gets is determined as the value minus the price paid. In the present environment, however, such a presentation seemed inappropriate, because some subjects (especially when they were in the conservative scenarios) would have much worse opportunities to earn money than others. Further, the non-linearity of the valuation functions would have made it tedious to compute the actual payoff consequences from the auction outcome and the money spent. To tackle both problems, we designed payoff tables for each bidder in each of the altogether eight scenarios. They contained money payoffs that had the number of MHz purchased and the percentage of the budget spent as dimensions (notice that the budget was a random draw from a given range even within a scenario). Further, bonus payoffs were provided for the additional goals that should be pursued in some scenarios (buying not less than the major rival, or inflating the competitors' prices). Hence, the payoff scheme chosen for the

[8] The auction design provided the right to withdraw from the purchase for D band operators in case of winning 2.4 MHz or less.

experiment did not correspond to a traditional simple valuation setup as typically used in auction experiments. The multiplicity of bidder's goals and the non-linearities in valuations that had emerged as stable structural elements in our extensive interviews made this departure from traditional experimentation necessary.

V. The Experiment with Student Subjects

In the experimental sessions with students, student subjects recruited on the university campus played the role of the bidders. The auction is held as a "replicate" of the real auction, using essentially the same rules. Naturally, some modifications are necessary, since the real spectrum auction was scheduled for several days, while in the experimental session a number of consecutive auctions is played within a few hours. To speed up the auction process, the decision time was shortened and the minimum bid was set higher in relation to the bidders' budgets than it was expected to be in the real auction. Further, the minimum bidding increment was set to 20%.

The experiments were computerised with software developed using *RatImage* (Abbink and Sadrieh (1995)). The subjects filled in an on-screen form in which they typed in their bids for the ten items, and then pressed a button to submit all bids simultaneously. The decisions are transmitted to a control terminal, whose software makes all necessary calculations, and sends the feedback to the subject terminals. Once the session is started, the auction is conducted fully automatically. Compared to experiments run by hand, computerised experiments allow a much speedier conduct of the experiment.

In most cases spectrum auctions are relatively complex. Therefore, a sufficient number of subsequent auctions should be played within a session, in order to enable subjects to get acquainted with the mechanism, and to adapt their behaviour to the strategic environment. The duration of the experiment is the limiting factor in this respect. In the present case, we could conduct five consecutive auctions in the three hours scheduled for each session.[9]

The subjects were given detailed instructions at the outset of an experimental session. Written hand-outs explained the rules of the auction and the scenarios. No reference was made to the spectrum auction scenario underlying the experiment. The subjects simply set out for "lots" and were called "bidder A" to "bidder D". The set of possible scenario combinations was common knowledge, but each subject only knew the scenario the own "bidder" was in and not the scenarios of the other three "bidders."

Four groups played in parallel in each session. Each of the four groups played five consecutive auctions in the course of the session. We decided to drop the first of the five auctions played by each group, the one in which subjects were very inexperienced, from our data analysis. The eight scenarios under consideration were distributed over the sessions and the consecutive auctions in the

[9] Even longer sessions may deteriorate the results as subjects' ability to concentrate on the problem may decline.

following manner. Each scenario combination was envisaged to be played eight times in eight different markets, but no combination was played more than once by the same subjects. This was done to gather eight independent observations for each scenario combination. Further, care was taken that each scenario combination was played as second, third, fourth, and fifth of the consecutive auctions the same number of times (the combination for the first auction could be chosen arbitrarily, as this was not used for the data analysis). Therefore, we ensured that all scenario combinations were played under the same circumstances, and that the results from single scenario combinations were not biased because of predominantly inexperienced subjects in one combination.[10] Four experimental sessions with a total of 64 subjects were conducted. When the experiment was conducted, it turned out that many groups played slightly faster than expected. In these cases, we ran an additional (sixth) auction, using a different scenario the respective group had not played before. As a result, we could gather between 10 and 12 observations for each scenario.

VI. Experiments within the Company

In parallel to the experimental sessions with student subjects, we conducted experiments with executives from the company. Experimental sessions with company managers cannot be conducted with the same methodological rigour as the laboratory sessions with students. The number of observations that can be gathered is naturally very limited, since the number of high-level managers who can arrange to find the time for participation in the experiment is very small. Therefore, only a handful of auctions could be played, all in the same scenario.

Nevertheless, these staff experiments are very important, for several reasons. Firstly, these experiments already serve as training sessions, since the managers in charge of the preparation for the auction are participants in the experiment. Secondly, they are reassuring for the validity of the results gathered in the student sessions. As in earlier studies (e.g. Dyer, Kagel, and Levin 1989), the comparison of students' to professionals' behaviour in our experiment revealed no substantial differences.

The experiments were conducted in the headquarters of the company. Telecommunications operators are usually not equipped with experimental laboratories, but nevertheless comparable controlled conditions could be installed. The software was installed on computers in the managers' offices, which were interconnected via the local network. The managers typically played in teams. A further difference to the student sessions was that subjects were not paid according to their success. This seemed unnecessary because the managers' professional involvement ensured a high degree of intrinsic motivation.

In general, the same set-up and the same presentation as in the experiments with students were used. Only in details, changes had been applied. These in-

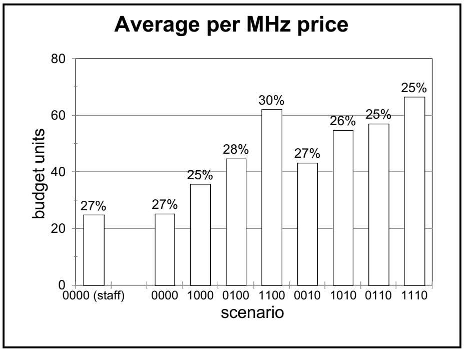
[10] Notice that full statistical independence for a comparison over the scenario combinations cannot be achieved. However, such a comparison between treatments was not the focus of our research anyway.

volve the scaling of the budget constraints and the sequence in which the bidders appear on the screen. For the student sessions these details had been rearranged in order to prevent possible inference on critical information.[11]

VII. Experimental Results

The experimental data collected in the student and the staff sessions were analysed in order to learn lessons for the company's bidding strategy. Figure 1 shows the average price per MHz in each of the eight scenario combinations.[12] Figure 2 shows the allocation of MHz to the four bidders in the auction, disaggregated over the single auctions played within the scenario combinations. The notation for the scenario combination is as follows: Sorted by bidders, from A to D, the name contains a "0" for a conservative bidder and a "1" for an expansive bidder. In the scenario combination 1100, for example, bidders A and B are expansive, while bidders C and D are conservative.

Figure 1



Note: The labels indicate average prices as percentage of the average budgets in the corresponding scenarios.

[11] Of course, it was extremely unlikely that any of the student subjects had any connection to a person in charge of a competitor's preparations for the auction.

[12] The scale of budget units is completely arbitrary, as it was used in the student sessions. The prices should not be taken as being equivalent to any real world currency.

The analysis of the data revealed the following stylised facts.

1. Both in the student sessions and in the staff sessions the bidding was very competitive. Subjects went for all ten units in the beginning and typically reduced their bidding rights only when the budget limit forced them to do so. This generated fairly high per MHz prices that on average were greater than one fourth of bidders' budgets. As can easily be seen in figure 1, the more expansive bidders are involved in a scenario combination, the higher is the average price per unit. Especially, when the D band operators are in their expansive scenarios, prices increase dramatically. Comparing the scenario combinations 0000, 1000, and 1100, one observes that the price per MHz increases by about fifty percent in each step. Since this roughly coincides with the increase in the total budget available to the four contestants, on average the fraction of the budget spent on one MHz ranged between 25 and 30 percent in all scenarios.

2. Attempts to raise the competitors' prices, which at first sight seemed to be easy due to the fragmented packaging, were generally unsuccessful. They typically lead to unwanted purchases of single units. This can be seen in figure 2. In the scenario combinations in which the E band operators have such a motivation (the scenarios xx10), they tend to purchase positive quantities.

3. When two or three expansive bidders are in the market, the bidder with the third highest budget has the most difficult task. Typically, these scenario combinations lead to all buyers purchasing relatively few items. Figure 2, scenario combination 1110 shows the outcome for the case with three expansive bidders, the figure for scenario combinations 0110, 1100, and 1010 depict the cases with two expansive bidders.

4. Expansive bidders attempting to buy all or most of the frequencies face a significant exposure problem. They typically fail, but often do not manage to quit in time, and then finish with relatively few items, which are largely useless to them. One of the D band operators and one of the E band operators were assumed to pursue such a goal in their expansive scenarios. However, very rarely does an expansive bidder manage to purchase all spectrum (even if he is the only expansive bidder). In the presence of two or more expansive bidders, it appears very difficult to obtain substantially more than half of all available spectrum.

VIII. Training Sessions

In the further process of the auction preparation, another set of training sessions should be held, supplementing the experimental sessions within the company described in section 7. This is important because at that stage of the process, reflections on the bidding strategy were still at a very early stage. After the experiments have been analysed and a bidding strategy has been developed, it is important that the bidding strategy is tested, revised and fine-tuned. This process should be performed on the basis of own training experience.

Figure 2

Allocation of Spectrum

Note: Each bar depicts the number of units bought by a bidder in a session of a scenario.

In the training sessions, the actual bidding team should play together taking the role of the own company in the auction. The other roles should be played by other company members, preferably not by the advisors or the managers immediately responsible for the preparation of the auction. This is because the bidding team should face a situation in which it is uncertain about the behaviour of the other players, and the behaviour of the other bidders is not "streamlined" with respect to the own company's bidding strategy.

The training sessions revealed that it would be very useful to be informed about the other bidders' bidding eligibility during the bidding process. The auction design did not provide any feedback on this, since only the highest bids were publicised. Thus, it was generally not possible to know the exact current bidding eligibility of other bidders during the auction. However, the design allowed for some inference to be drawn in the course of the auction.

IX. Bidding Eligibility Software

In the beginning of the auction, every bidder has a bidding eligibility of ten units, which can later only decrease once the bidder's number of active bids has fallen. It is straightforward to see that if the holder and the current price of an item remain unchanged in a given bidding round, then all other bidders have not actively bid for that item. Thus the number of active bids of all other bidders cannot be greater than 10 minus the number of items with unchanged price and holder.

However, even if all items change holder and price in a given bidding round, some inference can be drawn on the bidding eligibility of other bidders. This is due to the tie-breaking rule applied in the auction. If two bidders submit the same bids for an item (this is likely if bidders increase the current price only by the minimum increment), then the bidder who submitted the bid first becomes the temporary holder of the item. If we observe that the prices of different items have increased only by the minimum increment, but different items have different holders, then we can infer that the bidding eligibility of at least one of the bidders is less than maximum. Suppose, for example, we observe that in one bidding round all items' current prices have increased by the minimum increment, but bidder A is holder of five lots, and bidder B is standing high on the remaining five items. Then we can infer that either bidder A or bidder B is down to a bidding eligibility of 5 items (plus the number of items this bidder has held in the previous round), because otherwise the faster of the two would have become holder of the remaining units as well. We do not know who of the two bidders has a reduced bidding eligibility at that stage. However, in a later round this question may be resolved. Suppose, for example, that a few rounds later bidder A shows up as the holder of six or more units. At that point, we then know that bidder B had been faster than bidder A in that earlier round, but had bid only for five units. Since a bidder's number of active bids cannot increase, we then know that bidder B's eligibility cannot be greater than five anymore.

Inferring other bidders' maximum bidding eligibility requires to track the complete auction history of the auction, since sometimes information from many rounds before may be required to extract the maximum possible information. Further, many possible constellations must be considered. Therefore, we developed a software tool that calculated and displayed minimum and maximum possible bidding eligibility in every round, based on the history of the auction.

X. The Bidding Strategy

After the training sessions have been held, the bidding strategy can be finalised. It is essential that the bidding strategy is as much as possible a *strategy* in the game theoretic sense, a plan that prescribes moves for *every* situation that can possibly come up in the game. "Cold" decisions are preferable to "hot" decisions; there should be as little need as possible for spontaneous unprepared actions during the auction. Decision time in the auction is often very limited; choices made in the heat of the moment may not be well-reflected.

From the lessons learnt in the experiment, we developed a bidding strategy recommendation. The bidding strategy comprises of the entry bid, bid levels at which bidding eligibility is to be given up, and a final decision when to quit the auction. The experimental data was used to check the robustness of the strategy, i.e. to assess the variance of its profitability when played against experimentally observed types of bidding behaviour. Especially, the observed behaviour of the experienced subjects provided valuable information on the set of possible and probable types of bidding behaviour. A main requirement was that the recommended strategy should lead to a minimum aspired payoff without being vulnerable to predatory behaviour of others. The performance of the recommended strategy in this respect was not only assessed empirically in the training sessions, but was also subject to a rough theoretical evaluation. Due to the complexity of the environment, the theoretical evaluation had to be restricted to the examination of some of the strategic implications of bidding behaviour, instead of pursuing a full-fledged game equilibrium. Confidentiality requirements do not allow us to reveal details about the company's bidding strategy or budget decisions.

XI. Summary

The design of a spectrum auction is important for both the government as the seller and the bidders as the potential buyers. While the seller must customise the design according to its specific goals (efficiency, competition, or revenue), the buyers typically face the challenge to tailor their bidding strategy for a given auction design to the company's goals. Both tasks require a careful strategic analysis of the various alternatives. Behavioural regularities induced by the design of an auction must be taken into account.

The behavioural approach can be applied to both the design of an auction as well as to the implementation of a bidding strategy. This paper reports a case study in which we assisted a bidder in the German DCS1800 auction in the preparation for its bidding. We describe the various steps on this path: First, information that may be scattered in the company must be collected and aggregated. From the relevant influential factors, likely scenarios are worked out. These scenarios are the basis for creating the experimental environment for experimental sessions with student subjects. Accompanying sessions are held with company managers, which also serve as first training sessions for the decision makers in the company. The lessons learnt from the data analysis and from the managers' experiences are integrated into the implementation of a bidding strategy, complemented by theoretical considerations. Finally, training sessions are held to apply the bidding strategy in trial auctions.

XII. Epilogue: The Auction Outcome

The DCS-1800 auction was held in September 1999 in RegTP premises in Mainz. Though it was scheduled for up to three days, the auction eventually lasted only 1½ hours and was finished after three bidding rounds. In the first bidding round, MMO submitted the highest bids for all ten items. MMO held lots 1-5 with a current bid of DM 36.36m, the lots 6-9 with DM 40m, and lot 10 – the 2×1.4 MHz block – with DM 56m. Notice that the lots 1-9 are perfectly homogeneous, but MMO submitted differentiated bids. After the second round, T-Mobil held lots 1-4 for DM 40.01m, lot 5 for DM 40m; MMO was still holder of the second five lots. Notice that the latter implies that T-Mobil had not attempted to overbid MMO on lots 6-10. E-plus and Viag Interkom had quit the auction. In the final third round, no new bids were submitted, and the auction ended with a total revenue of DM 416.04m.

The auction results allow various interpretations. Without claiming to have the "right" story, we give one possible account of the observed auction outcomes that seems closely related to our experimental results. First, the observed bidding behaviour suggests that both T-Mobil and MMO had been in the conservative scenario, i.e. had falling marginal valuations for the new spectrum. Both MMO's first round bid as well as T-Mobil's response clearly indicate that both companies were not aiming at outbidding their competitors on all ten blocks. Secondly, the MMO bid indicated some sort of a priority for having the lots 6-10 rather than the lots 1-5. T-Mobil's 2nd bid showed that T-Mobil was satisfied acquiring the relatively cheaper lots 1-5. In this way, the lots were quickly distributed with little conflict. Note that the low frequency of bids from the extra-marginal bidders may indicate that the price at which the lots were bought was relatively high compared to the willingness-to-pay of the extra-marginal bidders. Notice also that no communication between the companies' managers is necessary to achieve this type of allocation.[13] Thirdly, the entry bid of MMO was well above the minimal bidding requirement, possibly to make sure that the bids would be visible. Another plausible reason for a high jump bid is that the rules provided two ways the auction could end, as described in section 3. It could either end because no new bids are submitted, or by announcement by the auc-

[13] This is also emphasised by *Grimm*, *Riedel*, and *Wolfstetter* (2001). In a game theoretical analysis of the German DCS-1800 auction the authors find that similar outcomes are obtained in a completely non-co-operative framework.

tioneer. The latter was possible after 20 rounds. It is conceivable that the high jump bid attempted at avoiding the end of the auction through a final sealed-bid stage.

Summary

The behavioural approach can be applied to both the design of an auction as well as to the implementation of a bidding strategy. This paper reports a case study in which we assisted a bidder in the German DCS1800 auction in the preparation for its bidding. We describe the various steps on this path: First, information that may be scattered in the company must be collected and aggregated. From the relevant influential factors, likely scenarios are worked out. These scenarios are the basis for creating the experimental environment for experimental sessions with student subjects. Accompanying sessions are held with company managers, which also serve as first training sessions for the decision makers in the company. The lessons learnt from the data analysis and from the managers' experiences are integrated into the implementation of a bidding strategy, complemented by theoretical considerations. Finally, training sessions are held to apply the bidding strategy in trial auctions.

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Appendix

The Instructions for the Auction Experiment

Lots and Bidders

- In this auction you can bid for 10 different lots: **lot 1, lot 2, …, lot 10**.
- Each lot is characterised by a *capacity*. Lot 1 to lot 9 have a capacity of 1000 and lot 10 has a capacity of 1400.
- There are 4 **bidders** in this auction: A, B, C, and D. The bidders differ in their aims they pursue in the auction and in their budget they are allowed to spend.

Rounds

- The auction is organised in consecutive rounds in which bidders can make their bids.
- Each rounds lasts for at least 5 minutes.
- A round ends if either

  all bidders have submitted their bids

  or the time limit is over.

Valid Bids

- In the first round of the auction the **minimal bid** is fixed for each lot. In all other rounds the minimal bid is *x* percent higher as the highest bid for this lot in the previous round. The percentage *x* chosen from the range 2 to 20 by the auctioneer and is announced in the beginning of each round. In the first round the value of *x* is 20.
- It is not possible to withdraw a submitted bid.
- In each round each bidder has to take care that his budget is higher than the sum of his new bids added to the bids for those lots, for which he is the current holder.

Highest Bids

- At the end of one round for each lot the bidder is determined who has submitted the highest bid for that lot. This bidder is called the holder of the highest bid for that lot.
- If more than one bidder have submitted the highest bid for the same lot, the bidder, who submitted his bid first, becomes the holder of that lot.

Active Bids

- In the first round each bidder is allowed to bid for all 10 lots.
- In the following rounds the number of active bids of one bidder is not allowed to exceed the number of his active bids in the previous round.
- A bidder has an active bid on a certain lot, if either in the beginning of the current round he is its holder or he submits a bid for that lot in this round.

Information in Each Round

- Each bidder is provided with the following information concerning the **previous round**:

  the highest bid for each lot

  the holder of the highest bid for each lot those lots for which you are the holder are displayed in red colour.

- Each bidder is provided with the following information concerning the **current round**:

  the minimal bid for each lot.

End of the Auction

- The current round is the last round of the auction (i.e. the auction ends) if either

  the auctioneer determines an early end of the auction,

  or none of the bidders submits a new bid in the current round.

- The bidder who is the holder of a lot in the last round wins this lot.

An Early End of the Auction

- After 20 rounds the auctioneer is able to reduce the auction to two further rounds.

Number of Auctions

- We try to complete 5 auctions.

Aims and Budgets of bidders

- For each bidder there are two possible scenarios: 0 and 1. Before an auction the scenario for the current auction for each bidder is randomly and independently determined with an equal probability for each scenario. A bidder is only informed about his own scenario.
- Each scenario contains a budget range, from which the budget is randomly and independently determined while all possible values could occur with the same probability.
- The scenarios differ in their budget ranges and in the aims of the bidders.

<table>
<tr><td colspan="2">Bidder A</td></tr>
<tr><th>Scenario 0</th><th>Scenario 1</th></tr>
<tr><td colspan="2">Bidder A aims to win as many lots as possible, under the constraints that
• a capacity of less than 2400 is worthless for him
• the increase in value per capacity unit decreases after 5000, i.e. it is most important for him to win at least a capacity of 5000

Bidder A aims to prevent that Bidder B obtains a capacity which is more than 1600 higher than his own capacity.</td></tr>
<tr><td>Budget range: 750 – 1500</td><td>Budget range: 1800 - 3800</td></tr>
</table>

<table>
<tr><td colspan="2">Bidder B</td></tr>
<tr><th>Scenario 0</th><th>Scenario 1</th></tr>
<tr><td>Bidder B aims to win as many lots as possible, under the constraints that
• a capacity of less than 2400 is worthless for him
• the increase in value per capacity unit decreases after 5000, i.e. it is most important for him to win at least a capacity of 5000
Bidder B aims to prevent that Bidder A wins a higher capacity than he himself.</td><td>Bidder B aims to win as many lots as possible, under the constraints that
• a capacity of less than 2400 is worthless for him
• the increase in value per capacity unit increases after 5000, i.e. it is most important for him to win a capacity higher than 5000
Bidder B aims to prevent that Bidder A wins a higher capacity than he himself.</td></tr>
<tr><td>Budget range: 900 – 1900</td><td>Budget range: 3350 - 5700</td></tr>
</table>

<table>
<tr><td colspan="2">Bidder C</td></tr>
<tr><th>Scenario 0</th><th>Scenario 1</th></tr>
<tr><td>Bidder C aims to win as many lots as possible if lots are cheap. For him a substantial increase in value per capacity unit starts with a capacity higher than 5000.
If it is not possible to obtain a capacity of at least 5000 for little money, bidder C prefers to rise the price for the other bidders and tries to obtain as few as possible lots for himself.</td><td>Bidder C aims to win as many lots as possible if lots are cheap. For him a substantial increase in value per capacity unit starts with a capacity higher than 5000.</td></tr>
<tr><td>Budget range: 350 – 950</td><td>Budget range: 2050 – 4100</td></tr>
</table>

Bidder D	
Scenario 0	**Scenario 1**
Bidder D tries to rise the price for the other bidders and prefers to obtain as few as possible lots for himself. Only if lots are very cheap, bidder D aims to win as many lots as possible.	Bidder D aims to win as many lots as possible if lots are cheap. For him a substantial increase in value per capacity unit starts with a capacity higher than 5000.
Budget range: **350 – 650**	Budget range: **1600 – 3200**

Bidder A **Scenario 0 and Scenario 1**

fraction of budget spent / MHz bought	1000	1400	2000	2400	3000	3400	4000	4400	5000	5400	6000	6400	7000	7400	8000	8400	9000	9400	10000
10%	-100	-100	-100	400	700	900	1200	1400	1700	1740	1800	1840	1900	1940	2000	2040	2100	2140	2240
20%	-200	-200	-200	300	600	800	1100	1300	1600	1640	1700	1740	1800	1840	1900	1940	2000	2040	2140
30%	-300	-300	-300	200	500	700	1000	1200	1500	1540	1600	1640	1700	1740	1800	1840	1900	1940	2040
40%	-400	-400	-400	100	400	600	900	1100	1400	1440	1500	1540	1600	1640	1700	1740	1800	1840	1940
50%	-500	-500	-500	0	300	500	800	1000	1300	1340	1400	1440	1500	1540	1600	1640	1700	1740	1840
60%	-600	-600	-600	-100	200	400	700	900	1200	1240	1300	1340	1400	1440	1500	1540	1600	1640	1740
70%	-700	-700	-700	-200	100	300	600	800	1100	1140	1200	1240	1300	1340	1400	1440	1500	1540	1640
80%	-800	-800	-800	-300	0	200	500	700	1000	1040	1100	1140	1200	1240	1300	1340	1400	1440	1540
90%	-900	-900	-900	-400	-100	100	400	600	900	940	1000	1040	1100	1140	1200	1240	1300	1340	1440
100%	-1000	-1000	-1000	-500	-200	0	300	500	800	840	900	940	1000	1040	1100	1140	1200	1240	1340

Bidder A receives a bonus of 500, if he does not purchase more than 1600 units less than Bidder B.

Bidder B Scenario 0

fraction of budget spent

MHz bought	1000	1400	2000	2400	3000	3400	4000	4400	5000	5400	6000	6400	7000	7400	8000	8400	9000	9400	10000
10%	-100	-100	-100	400	700	900	1200	1400	1700	1740	1800	1840	1900	1940	2000	2040	2100	2140	2240
20%	-200	-200	-200	300	600	800	1100	1300	1600	1640	1700	1740	1800	1840	1900	1940	2000	2040	2140
30%	-300	-300	-300	200	500	700	1000	1200	1500	1540	1600	1640	1700	1740	1800	1840	1900	1940	2040
40%	-400	-400	-400	100	400	600	900	1100	1400	1440	1500	1540	1600	1640	1700	1740	1800	1840	1940
50%	-500	-500	-500	0	300	500	800	1000	1300	1340	1400	1440	1500	1540	1600	1640	1700	1740	1840
60%	-600	-600	-600	-100	200	400	700	900	1200	1240	1300	1340	1400	1440	1500	1540	1600	1640	1740
70%	-700	-700	-700	-200	100	300	600	800	1100	1140	1200	1240	1300	1340	1400	1440	1500	1540	1640
80%	-800	-800	-800	-300	0	200	500	700	1000	1040	1100	1140	1200	1240	1300	1340	1400	1440	1540
90%	-900	-900	-900	-400	-100	100	400	600	900	940	1000	1040	1100	1140	1200	1240	1300	1340	1440
100%	-1000	-1000	-1000	-500	-200	0	300	500	800	840	900	940	1000	1040	1100	1140	1200	1240	1340

Bidder B Scenario 1

fraction of budget spent

MHz bought	1000	1400	2000	2400	3000	3400	4000	4400	5000	5400	6000	6400	7000	7400	8000	8400	9000	9400	10000
10%	-100	-100	-100	260	350	410	500	560	920	1160	1520	1760	2120	2360	2720	2960	3320	3560	4160
20%	-200	-200	-200	160	250	310	400	460	820	1060	1420	1660	2020	2260	2620	2860	3220	3460	4060
30%	-300	-300	-300	60	150	210	300	360	720	960	1320	1560	1920	2160	2520	2760	3120	3360	3960
40%	-400	-400	-400	-40	50	110	200	260	620	860	1220	1460	1820	2060	2420	2660	3020	3260	3860
50%	-500	-500	-500	-140	-50	10	100	160	520	760	1120	1360	1720	1960	2320	2560	2920	3160	3760
60%	-600	-600	-600	-240	-150	-90	0	60	420	660	1020	1260	1620	1860	2220	2460	2820	3060	3660
70%	-700	-700	-700	-340	-250	-190	-100	-40	320	560	920	1160	1520	1760	2120	2360	2720	2960	3560
80%	-800	-800	-800	-440	-350	-290	-200	-140	220	460	820	1060	1420	1660	2020	2260	2620	2860	3460
90%	-900	-900	-900	-540	-450	-390	-300	-240	120	360	720	960	1320	1560	1920	2160	2520	2760	3360
100%	-1000	-1000	-1000	-640	-550	-490	-400	-340	20	260	620	860	1220	1460	1820	2060	2420	2660	3260

Bidder B receives a bonus of 500, if he purchases at least as many units as Bidder A.

Bidder C **Scenario 0**

MHz bought	1000	1400	2000	2400	3000	3400	4000	4400	5000	5400	6000	6400	7000	7400	8000	8400	9000	9400	10000
fraction of budget spent 10%	-100	-60	0	40	100	140	200	240	700	780	900	980	1100	1180	1300	1380	1500	1580	1780
20%	-200	-160	-100	-60	0	40	100	140	600	680	800	880	1000	1080	1200	1280	1400	1480	1680
30%	-300	-260	-200	-160	-100	-60	0	40	500	580	700	780	900	980	1100	1180	1300	1380	1580
40%	-400	-360	-300	-260	-200	-160	-100	-60	400	480	600	680	800	880	1000	1080	1200	1280	1480
50%	-500	-460	-400	-360	-300	-260	-200	-160	300	380	500	580	700	780	900	980	1100	1180	1380
60%	-600	-560	-500	-460	-400	-360	-300	-260	200	280	400	480	600	680	800	880	1000	1080	1280
70%	-700	-660	-600	-560	-500	-460	-400	-360	100	180	300	380	500	580	700	780	900	980	1180
80%	-800	-760	-700	-660	-600	-560	-500	-460	0	80	200	280	400	480	600	680	800	880	1080
90%	-900	-860	-800	-760	-700	-660	-600	-560	-100	-20	100	180	300	380	500	580	700	780	980
100%	-1000	-960	-900	-860	-800	-760	-700	-660	-200	-120	0	80	200	280	400	480	600	680	880

In Scenario 0 bidder C receives a bonus of 20% of the total turnover of the other bidders.

Bidder C **Scenario 1**

MHz bought	1000	1400	2000	2400	3000	3400	4000	4400	5000	5400	6000	6400	7000	7400	8000	8400	9000	9400	10000
fraction of budget spent 10%	-100	-60	0	40	100	140	200	240	940	1140	1440	1640	1940	2140	2440	2640	2940	3140	3640
20%	-200	-160	-100	-60	0	40	100	140	840	1040	1340	1540	1840	2040	2340	2540	2840	3040	3540
30%	-300	-260	-200	-160	-100	-60	0	40	740	940	1240	1440	1740	1940	2240	2440	2740	2940	3440
40%	-400	-360	-300	-260	-200	-160	-100	-60	640	840	1140	1340	1640	1840	2140	2340	2640	2840	3340
50%	-500	-460	-400	-360	-300	-260	-200	-160	540	740	1040	1240	1540	1740	2040	2240	2540	2740	3240
60%	-600	-560	-500	-460	-400	-360	-300	-260	440	640	940	1140	1440	1640	1940	2140	2440	2640	3140
70%	-700	-660	-600	-560	-500	-460	-400	-360	340	540	840	1040	1340	1540	1840	2040	2340	2540	3040
80%	-800	-760	-700	-660	-600	-560	-500	-460	240	440	740	940	1240	1440	1740	1940	2240	2440	2940
90%	-900	-860	-800	-760	-700	-660	-600	-560	140	340	640	840	1140	1340	1640	1840	2140	2340	2840
100%	-1000	-960	-900	-860	-800	-760	-700	-660	40	240	540	740	1040	1240	1540	1740	2040	2240	2740

Bidder D — Scenario 0

fraction of budget spent \ MHz bought	1000	1400	2000	2400	3000	3400	4000	4400	5000	5400	6000	6400	7000	7400	8000	8400	9000	9400	10000
10%	-100	-60	0	40	100	140	200	240	300	340	400	440	500	540	600	640	700	740	840
20%	-200	-160	-100	-60	0	40	100	140	200	240	300	340	400	440	500	540	600	640	740
30%	-300	-260	-200	-160	-100	-60	0	40	100	140	200	240	300	340	400	440	500	540	640
40%	-400	-360	-300	-260	-200	-160	-100	-60	0	40	100	140	200	240	300	340	400	440	540
50%	-500	-460	-400	-360	-300	-260	-200	-160	-100	-60	0	40	100	140	200	240	300	340	440
60%	-600	-560	-500	-460	-400	-360	-300	-260	-200	-160	-100	-60	0	40	100	140	200	240	340
70%	-700	-660	-600	-560	-500	-460	-400	-360	-300	-260	-200	-160	-100	-60	0	40	100	140	240
80%	-800	-760	-700	-660	-600	-560	-500	-460	-400	-360	-300	-260	-200	-160	-100	-60	0	40	140
90%	-900	-860	-800	-760	-700	-660	-600	-560	-500	-460	-400	-360	-300	-260	-200	-160	-100	-60	40
100%	-1000	-960	-900	-860	-800	-760	-700	-660	-600	-560	-500	-460	-400	-360	-300	-260	-200	-160	-60

In Scenario 0 bidder D receives a bonus of 20% of the total turnover of the other bidders.

Bidder D — Scenario 1

fraction of budget spent \ MHz bought	1000	1400	2000	2400	3000	3400	4000	4400	5000	5400	6000	6400	7000	7400	8000	8400	9000	9400	10000
10%	-100	-60	0	40	100	140	200	240	940	1140	1440	1640	1940	2140	2440	2640	2940	3140	3640
20%	-200	-160	-100	-60	0	40	100	140	840	1040	1340	1540	1840	2040	2340	2540	2840	3040	3540
30%	-300	-260	-200	-160	-100	-60	0	40	740	940	1240	1440	1740	1940	2240	2440	2740	2940	3440
40%	-400	-360	-300	-260	-200	-160	-100	-60	640	840	1140	1340	1640	1840	2140	2340	2640	2840	3340
50%	-500	-460	-400	-360	-300	-260	-200	-160	540	740	1040	1240	1540	1740	2040	2240	2540	2740	3240
60%	-600	-560	-500	-460	-400	-360	-300	-260	440	640	940	1140	1440	1640	1940	2140	2440	2640	3140
70%	-700	-660	-600	-560	-500	-460	-400	-360	340	540	840	1040	1340	1540	1840	2040	2340	2540	3040
80%	-800	-760	-700	-660	-600	-560	-500	-460	240	440	740	940	1240	1440	1740	1940	2240	2440	2940
90%	-900	-860	-800	-760	-700	-660	-600	-560	140	340	640	840	1140	1340	1640	1840	2140	2340	2840
100%	-1000	-960	-900	-860	-800	-760	-700	-660	40	240	540	740	1040	1240	1540	1740	2040	2240	2740