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ABSTRACT

Strange Bids: Bidding Behaviour in the United Kingdom's Third Generation Spectrum Auction*

This Paper studies bidding behaviour in the auction of radio spectrum for third generation mobile telephone services which took place in the United Kingdom in the spring of 2000. We show that several companies' bidding behaviour deviates strongly from theoretical predictions. In particular some companies' evaluation of the added advantage of having a large license rather than a small license seemed to change dramatically during the auction for no obvious reason. We conclude that it is less well understood than previously believed how spectrum auctions work, and whether they lead to an efficient allocation of spectrum.

JEL Classification: D44
Keywords: private value, simultaneous ascending auction and third generation spectrum auction

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Submitted 30 October 2001

1 Introduction

The Purpose of This Paper

Many countries around the world have recently used auctions to award licences for the operation of mobile telephone services. A variety of different auction formats have been employed. The experience from these auctions provides a wealth of information which can be used to assess the appropriateness of auctions in general, and of different auction formats in particular, for the award of licences in the mobile telephone and other sectors. The purpose of this paper is to contribute to the analysis of the available evidence. We shall focus on one particular auction: the United Kingdom's sale of UMTS ("Universal Mobile Telecommunications Services") licences for third generation mobile telephone services in the Spring of 2000.

This auction was organised as a simultaneous ascending auction. The key features of a simultaneous ascending auction are that there are multiple rounds, new bids can be made in each round, bids are made openly, and all licences are sold simultaneously, i.e. the auction closes only when bidding on *all* licences has stopped.[3] The simultaneous ascending auction is currently the most popular auction format for the sale of spectrum (Cramton (2001)). It was originally developed by McAfee, Milgrom and Wilson for the sale of PCS ("Personal Communications Services") licences by the United States' Federal Communications Commission (FCC) between 1994 and 1996 [4] but has since been used in a variety of other auctions in the United States and other countries.[5]

There are several reasons why, among the simultaneous ascending spectrum auctions which have been conducted so far, the United Kingdom's auction is particularly suitable as a research subject. Firstly, the amounts of money involved were very large. At the time at which the auction occurred, the UK's newspapers called it the "biggest auction ever" (see Binmore and Klemperer (2001)).

[3] For an exposition of the theory and practice of simultaneous ascending auctions see Milgrom (2000).

[4] For an account of the development of the simultaneous ascending auction see McMillan (1994). A early version of the simultaneous ascending auction appears in Demange et. al. (1986).

[5] See, for example, the reviews of a variety of recent spectrum auctions in Cramton (2001), Grimm et. al. (2001), Jehiel and Moldovanu (2001), and Klemperer (2001)

A second reason for choosing this auction as a subject of research is that it was very transparent. Every bid and the identity of the corresponding bidder were made public after each round. This was true not just for the currently leading bids for each licence but also for all losing bids. It is this publicly available information on which our empirical analysis will be based.[6]

A third point which recommends the United Kingdom's auction as a subject for research is that the UK used the simultaneous ascending auction design in particularly simple circumstances. The main factor which made the UK's third generation auction a simple auction in comparison to other spectrum auctions is that each bidder could acquire at most one licence. By contrast, in the PCS auctions in the United States, for example, bidders could acquire more than one licence. The background to this is that licences in the UK were nationwide whereas in the United States they covered only limited geographical areas. In the US therefore bidders could acquire licences in several different areas. If bidders can acquire more than one licence several important complications result which did affect the US auctions but not the UK auctions. One such complication is that in the PCS auctions in the US possible synergies which a bidder could derive from acquiring licences in neighbouring areas played an important role in the auction design (McMillan (1994)), and evidence of such synergies can be found in the auction outcomes (Ausubel et. al. (1997)). The ability to bid for multiple licences also made certain collusive strategies possible where competitors linked their bidding behaviour for one licence with bids for some other licence, and there is some evidence that bidders adopted such strategies (Cramton and Schwartz (1999,2000)). Neither of these effects played a role in the UK auction.

In the UK five nationwide licences were for sale. The licences differed in the amount of spectrum assigned to them. Two licences (licences A and B) were "large", consisting of 15+15 MHz of paired spectrum. Licence A included, in addition, 5 MHz of unpaired spectrum. Three licences (licences C, D and E) were "small", consisting of only 10+10 MHz of paired spectrum and 5 Mhz of unpaired spectrum. The fact that the licences were not identical is a final aspect which makes this auction interesting. Much of our

[6] At the time of writing these data are still available at a webpage of the United Kingdom's Radiocommunications Agency: http://www.spectrumauctions.gov.uk/.

analysis focuses on the differences in values attached to large and small licences. The analysis would be impossible if the licences were identical.

Basic Hypotheses

The focus of our analysis will be on the question whether bidders' behaviour in the United Kingdom's UMTS auction is *easily rationalized*. By this we mean whether bidders' behaviour is compatible with the following three principles:

- Each bidder enters the auction with a fixed valuation for each licence, and this valuation is not affected by the events which occur during the auction.
- When choosing for which licence to bid bidders compare their valuation of each licence to the minimum bid that is needed to overbid the currently leading bid for that licence, and then pick the licence for which the difference, i.e. the surplus, is maximal.
- When bidding for a licence bidders place the smallest currently admissible bid.

In the terminology of auction theory the first bullet point says that we postulate a *private value model,* and the second and third bullet points say that we postulate *straightforward bidding.*[7] [8]

We emphasize immediately that we take these assumptions as our benchmark not because we have strong a priori grounds to believe these assumptions to be correct. For example, we recognize of course that contrary to the private value assumption bidders might infer from aggressive bidding by other bidders that their own initial valuations were too low. Similarly, we recognize the scope for much more strategic bidding than straightforward bidding. Indeed, our main finding in this paper will be that there are strong and systematic deviations of the observed behaviour from the

[7] The concept of *straightforward bidding* was introduced by Milgrom (2000) in the more general context of auctions where bidders can bid for more than one license. We adapt his terminology to our context.

[8] The three hypotheses which we investigate also underlie Plott and Salmon's (2001) independent analysis of the United Kingdom's UMTS auction. We give a detailed discussion of the relation between their work and ours in Section 2.

above principles. However, in our experience we learn more about our data by studying how they deviate from a simple benchmark than by trying to rationalize them on the basis of more complicated ideas.

Another important reason for focusing on this benchmark case is that it this the simplest scenario under which efficiency of the auction is guaranteed. In other scenarios it is no longer clear whether a simultaneous ascending auction guarantees efficiency. We use the term efficiency here in the following sense: licences are allocated to maximise the sum of the valuations of licence holders, subject to the constraint that each bidder can hold only one licence. That efficiency in this sense is achieved under straightforward bidding can be shown by adapting an argument which Milgrom has given for the more general case in which bidders can bid for more than one licence.[9]

Efficiency is of interest here because efficiency, not revenue maximisation, was the primary goal of the United Kingdom's government in the auction. This is made clear in the following statement made by the then Telecommunications Minister Barbara Roche to the House of Commons on 18 May 1998:

> "The Government's overall aim is to secure, for the long-term benefit of UK consumers and the national economy, the timely and economically advantageous development and sustained provision of UMTS services in the UK.
>
> Subject to this overall aim, the Government's objectives are to (i) utilise the available UMTS spectrum with optimum efficiency, (ii) promote effective and sustainable competition for the provision of UMTS services, and (iii) subject to the above objectives, design an auction which is best judged to realise the full economic value to consumers, industry and the taxpayer of the spectrum."[10]

Note that revenue appears only as the third objective and that it is clearly ranked

[9] Milgrom (2000), proof of Theorem 2. Milgrom shows that efficiency is achieved if an adjustment is made for the discreteness of the bid increases in the auction. We show in Appendix 2 how to adapt Milgrom's argument to our context.

[10] Quoted from the official Information Memorandum about the auction (Radiocommunications Agency and N. M. Rothschild & Sons (1999, p. 5)).

below the other two. To achieve its second objective the government set the number of licences equal to five, and, moreover, reserved the largest of these licences for an operator who was not at the time of the auction an incumbent in the UK's mobile telephone market. Given that this provision had already been made, the auction itself was primarily meant to achieve the first objective. We take this objective to be that the most efficient firms, i.e. the firms with the best business plans, should win the auction.

A further reason for focusing on the above benchmark case is that during the preparation period preceding the auction some of the advice which was offered to the United Kingdom's government and which was also revealed to the potential bidders was based on the private value assumption. In particular, the government's advisors reported to the government and to the bidders the results of experimental tests of different auction formats with student subjects. These experimental tests mimicked a private value set-up (UMTS Auction Consultative Group (1998) and (1999)).[11] Moreover, the reports offered to the government and to the bidders indicated that the experiments produced efficient allocations, and that this was in line with theoretical predictions. Presumably, these theoretical predictions were based on straightforward bidding.

Main Findings

Although the experiments apparently confirmed the hypotheses described above, our main finding in this paper is that the real bidders in the real auction did not confirm these hypotheses. Instead, we find large and systematic deviations from the behaviour predicted by these hypotheses. We find such deviations for some, but not for all bidders. Those bidders whose bids are irreconcilable with the above hypotheses deviate, moreover, in a very specific way from these hypotheses. Their bidding behaviour is inconsistent with a fixed assessment of the difference between the value of a "large" (licences A or B) and of a "small" (C, D or E) licence.

The private value assumption implies that bidders have a fixed assessment of this difference. Moreover, straightforward bidding implies that bidders will bid for a "large"

[11] We refer to the UMTS Auction Consultative Group documents because the detailed reports about the experiments are confidential.

licence only if the difference in the minimum bids for a large and a small licence is less than the difference in valuations. Now the difference between the minimum bid required to win a "large" licence and the minimum bid required to win a "small" licence grew significantly during the auction. Nonetheless, several bidders who initially stopped bidding for a "large" licence, and thus seemed to indicate that the bid difference had exceeded their valuation difference, later returned to bidding for a large licence. Such behaviour is inconsistent with our hypotheses.

We emphasize that the inconsistencies which we find concern not only the initial rounds of the auction but persist throughout the auction. This is important because one might see the bids in the initial rounds of the auction as irrelevant "gaming" arguing that bidders knew that prices would rise much higher.

An example is the bidding by British Telecom, one of the major incumbents in the United Kingdom's mobile telephone market. In round 17 of the auction British Telecom gave up bidding for a "large" licence and instead bid for a "small" licence. At this stage the difference in the minimum bids required for the two types of licences was £280 million. However, in round 142, when the difference was £ 1,860 million, British Telecom bid for a "large" licence. This is not easily rationalized.[12]

The main body of this paper documents such deviations from the hypotheses of straightforward bidding and private values. We also provide evidence to support our claim that these deviations were indeed the most significant deviations from the benchmark model, and that other aspects of bidding behaviour are more easily reconcilable with the benchmark model.

We also discuss alternative explanations of bidding behaviour in the auction. Consider for example the bids placed by British Telecom which were quoted above. One possible explanation could be that contrary to the private value assumption the very aggressive bidding by Vodafone for a big licence induced British Telecom to believe that the additional value of a big licence in comparison to a small licence was worth more than it had originally thought. We believe that, although this is logically possible, it is implausible. Note that the above figures indicate that British Telecom's estimate of the value difference multiplied by a factor of more than 6. It is hard to see how

[12] We discuss the bidding behaviour of British Telcom in more detail later in this paper.

other companies' bidding behaviour could lead to such a huge change in valuations. Other explanations which we consider are that British Telecom might have tried to raise the price which Vodafone had to pay for its licence, or that British Telecom's and other companies' bidding behaviour reflects differences of opinion in British Telecom's management. Of course, our discussion will not only apply to British Telecom but to other companies as well.

Policy Conclusions

What do we conclude from our analysis? Firstly, because the benchmark scenario is so clearly rejected, it is not obvious that efficiency was achieved in the auction. There is no known theoretical argument which would suggest that efficiency was achieved. Thus we question whether the widely held view that the United Kingdom's auction was an unambiguous success is supported by evidence.

Note, of course, that we do not assert the opposite, i.e. that the efficiency objective was *not* achieved. We do not have evidence to support such an assertion. We also emphasize that the question whether the United Kingdom's government fully achieved its objectives is different from the question whether the United Kingdom's government could have done better. We are in no position to answer this question either.

Our analysis suggests that advice offered to governments and to potential bidders must be cautious about the extent to which it promises full efficiency, and that it should not suggest that straightforward bidding is necessarily the correct solution to bidders' strategic problem.

Structure of This Paper

The remainder of this paper is organized as follows. Section 2 explains the background to the auction and the auction rules. Section 2 also discusses in detail the private value setup and the hypothesis of straightforward bidding. Finally, Section 2 contains a review of related literature. Section 3 is the core of the paper. We describe to which extent the observed bidding behaviour is compatible with our benchmark, and where it deviates from this benchmark. Finally, in Section 4, we discuss alternative rationalizations of the bidding behaviour which we observe, and we draw some

tentative conclusions from our analysis.

2 Background

This section contains three types of background material. Firstly, we provide some factual background about the auction and its outcome. Secondly, we discuss some aspects of the theoretical hypotheses of private values and straightforward bidding which we bring to our data. Finally, we review related literature.

The Auction

The licences sold by the United Kingdom's government were licences to use radio spectrum to deliver third generation mobile communications systems to customers. The licences on offer were UMTS licences. The UMTS forum, an organization of mobile telephone operators and other interested parties, describes UMTS services as follows: "UMTS will deliver pictures, graphics, video communications and other wide-band information as well as voice and data, direct to people who can be on the move" (UMTS Forum (2001)). More formally, UMTS is one in a family of systems which have been developed within the framework for third generation mobile communication introduced by the International Telecommunications Union (IMT).

The sale of UMTS licences in the United Kingdom was conducted by the "Radiocommunications Agency". This is an agency of the UK's government. The Radiocommunications Agency sold five licences, labeled A, B, C, D and E. Each licence entitles its owner to use a part of the spectrum that is identified in the licence. Licence A consisted of 15+15 MHz of paired spectrum and 5 MHz of unpaired spectrum. Licence B consisted of 15+15 MHz of paired spectrum. Licences C, D and E consisted of 10+10 MHz of paired spectrum and 5 MHz of unpaired spectrum. The licences are to remain in force until 2021. At the time of the auction licences could not be traded, but the government indicated that it might enable licence trading during the duration of the licences. The licences came with an obligation to roll out a network covering at least 80% of the UK population by 2007.[13]

[13] This paragraph and the next five paragraphs are based on Radiocommunications Agency and N.

Licence A was reserved for a new entrant into the UK's mobile phone market. The incumbent four mobile telephone operators of the UK were not allowed to bid for this licence. The four incumbent mobile telephone operators in the United Kingdom were: Vodafone, Cellnet (owned by British Telecom), Orange, and One2One. Their market shares on 1 May 1999 were: Vodafone (37.3%), Cellnet (30.1%), Orange (17.2%) and One2One (15.4%).[14]

The auction was organized in "rounds". In each round of the auction except the first round each licence had a "current price" and a "current price bidder". In each round the current price bidders had to remain inactive. All other bidders had three actions available to them. (1) They could place a bid for one of the licences. This bid had to exceed the "current price" by a minimum increment that was announced by the Radiocommunications Agency before the round began. (2) They could ask for a "waiver", i.e. do nothing. Each bidder could ask for a total of three waivers only in the auction. (3) They could withdraw from the auction. Withdrawal was final: a bidder who withdrew could not re-enter the auction.

The highest bid for each licence became the "current price" in the next round, and the bidder who placed that bid became the "current price bidder" in the next round. If no bid was placed on a licence then the "current price" and the "current price bidder" remained unchanged. If several bidders placed identical highest bids on a licence then the "current price bidder" was randomly selected from these bidders. The auction ended when the last bidder who was not "current price bidder" for some licence had withdrawn. Each "current price bidder" was then awarded their licence at the "current bid".

The minimum bids for the five licences in the first round were: A (£125 million) B (£107.1 Million.), C, D and E (£89.3 Million). In the first round all bidders had to be active and had to choose one of the three actions described above. In later rounds

M. Rothschild & Sons (1999). We neglect aspects which do not enter our analysis below. In particular, we do not explain the important arrangements concerning "associated bidders" since this issue will not feature in our investigation. For a detailed account of this issue and of other aspects of the auction see Binmore and Klemperer (2001).

[14]The indicated market shares are based on subscriber numbers, not revenue. Our source for the market share information is N. M. Rothschild & Sons (1999).

the minimum increment was x% of the current price, where x was initially 5, and was later chosen by the Radiocommunications Agency.

Interested bidders had to pay an initial deposit of £50 million. A bidder who wished to increase his bid to £400 million had to pay an additional deposit of £50 million. Winning bidders had the option to either pay the full amount immediately or to pay 50% initially and to pay the remainder in five installments starting in 2006, where a relatively large interest rate of 8.65 % was applied to calculate the size of the later installments.

What Happened?

The four incumbents entered the auction whereby BT Cellnet participated in the auction as BT3G. In addition, nine outsiders joined the auction: NTL Mobile, 3G UK, Worldcom, TIW, Telefonica, Spectrumco, Crescent, One.Tel, and Epsilon. The government agreed to regard these companies as independent bidders. Orange was owned by Mannesmann who, in turn, had just been taken over by Vodafone, but Vodafone had given an undertaking to the government to dispose of Orange after the auction, and to take measures which ensured the independence of Orange's bidding in the auction.

The auction opened on 6 March 2000 and closed on 27 April 2000. The number of rounds was 150. The typical number of rounds per day was five. The minimum increments by which a bidder had to overbid the previously highest bid was initially 5% but was lowered in several steps to 1.5%. Whenever a decision had been made to lower the minimum increments, this decision was implemented for any given licence only once one further bid at the old increment had been received for that licence. That is, for every licence the next bid still had to exceed the currently leading price by the old increment. The increment was lowered only after the next bid was made. A consequence was that the increment was not lowered for all licences in the same round. In particular, in round 133, or earlier, a decision was made to lower minimum increments to 1.5%. In round 134 a bid was received for licence E, and as a consequence the lower minimum increment was implemented for licence E. In subsequent rounds bids were received for almost all licences, and the minimum increments for these licences

was lowered. The only exception was licence A for which no further bid was received. Therefore, in the final round a bidder who wanted to bid for licence A had to raise the currently leading bid for licence A by 2.5% whereas for all other licences only an additional 1.5% had to be bid. Of course, the auction closed because no bidder was willing to place such bids.

The first company withdrew in round 94. All withdrawal decisions are listed in Table 2. We shall discuss withdrawal decisions in more detail in Section 3. The final winners of the auction, and the winning bids, are listed in Table 1.

Licence	Company	Winning Bid
A	TIW	£4,384.7 million
B	Vodafone	£5,964.0 million
C	BT3G	£4,030.1 million
D	One2One	£4,003.6 million
E	Orange	£4,095,0 million

Table 1: Winners

Company	Withdrew in Round
NTL Mobile	150
Telefonica	133
Worldcom	121
One.Tel	100
Epsilon	98
Spectrumco	97
3G UK	95
Crescent	94

Table 2: Withdrawals

All companies which won licences opted to pay for these licences immediately, and by September 2000 all licences had been issued by the government.

Is The Private Value Assumption Plausible?

As explained in the Introduction we plan to analyse the UK auction by comparing bidding behaviour to the behaviour that would have resulted in a so-called "private value" environment. By this, auction theory understands an environment in which at the beginning of the auction no bidder has private information which, if known to other bidders, would alter those bidders' valuations of licences (see McAfee and McMillan (1987)). The only type of private information which is admissible under this assumption is thus information which only affects the bidder in possession of the information, but which is irrelevant to other bidders.

For example it would be compatible with our private value assumption if some bidder had private information about his own labour costs, and if it were clear that this information is relevant to this bidder only, and does not affect any other bidder. By contrast, if some bidder had private information about the anticipated level of demand for third generation mobile telephone services which was not available to other bidders, then the private value assumption would be violated because other bidders' valuation would obviously be altered if they knew this information.

Although, as mentioned earlier, we do not intend to mount a strong defence of the private value assumption, we argue that it is not obviously inappropriate. At the time of the UK auction there had been long public discussions about the future potential of the UMTS technology, and about possible customers' demand for UMTS products. Clearly, these discussions had left a huge amount of uncertainty. However, it seems well possible that all relevant information had already reached the public domain, and that no firm had important insider information, except for information that concerned only its own situation, with no immediate relevance for other firms. If that is correct, then the private value assumption may well be a valid approximation.

Is Straightforward Bidding Rational?

What is "rational" in a strategic interaction like an auction can be defined in several ways. For example, one can ask whether a particular strategy is optimal independent of what the other players do. In such a case the strategy is called a "dominant strategy". Alternatively, one can ask whether a particular strategy is optimal if all the other agents adopt the same strategy. In that case game theory would call the strategy a

(symmetric) "equilibrium strategy". If a strategy is an equilibrium strategy then one can ask in addition whether it is the unique strategy with this property, or whether there are other equilibria of the game.

If a single object is auctioned in an ascending auction it is relatively obvious that under the private value assumption straightforward bidding[15], which in this case only requires to withdraw once the price reaches the private value, is a dominant strategy. In the case of multi-unit auctions the issue is more complicated and there are no general results in the literature yet.[16]

Straightforward bidding would clearly be optimal if (1) the auction closed in the next round, and if (2) a bidder who places a bid on a licence at the minimum admissible bid could be sure that this bid is successful. Consider the first condition. Clearly, the auction will typically *not* close in the next round. However, straightforward bidding might still be optimal if in case the auction does not close the bids placed today do not affect the future adversely. The current bid could have adverse effects for the future if other bidders were to condition their future behaviour on bids made today. But if all other bidders bid straightforwardly, then this will not be the case.

Notice that this argument is an equilibrium argument, not a dominance argument. The claimed optimality of straightforward bidding depends on the assumption that all other bidders bid straightforwardly. Notice also that the argument does *not* address the question whether there might be other equilibria. We elaborate the argument of the previous paragraph in some more detail, but without formalities, in Appendix 1.

Consider next the second implicit assumption which we made above, that bids which are equal to the minimum bid can be certain to be successful. This might be a self-destroying expectation, and thus not an equilibrium. If all other bidders bid straightforwardly, then there will be frequent ties. Now suppose that bidders condition

[15] The concept of *straightforward bidding* is defined in the Introduction.

[16] A significant part of the main theoretical paper on simultaneous ascending auctions (Milgrom (2000)), postulates in a more complicated context than ours straightforward bidding and studies its implications, without asserting that it is an equilibrium strategy. In other parts that paper investigates equilibrium strategies in examples the structure of which is different from that of the UK auction. The earlier Demange et. al. (1986) postulates straightforward bidding without proving it to be equilibrium behaviour.

on the assumption that the auction closes in the next round. Then, in order to increase their chances of obtaining their preferred object, bidders should place jump bids which exceed the minimum bid by some small amount. Thus, in this respect, straightforward bidding is not likely to be equilibrium behaviour. Therefore, when comparing observed bidding behaviour to our hypothesis of maintained bidding, we shall not attach much importance to the fact that bidders sometimes do not bid the minimum bid but make small jump bids.

Does Straightforward Bidding Guarantee Efficiency?

One argument which we gave in the Introduction to motivate our interest in the benchmark case of private values and straightforward bidding is that it is the simplest scenario in which the efficiency of the auction outcome is guaranteed. We shall now explain this claim in more detail.

Suppose we defined efficiency as "putting each licence into the hands of the bidder who values that licence the most". The simultaneous ascending auction does *not* achieve efficiency in this sense. For suppose the same bidder, say bidder 1, had the highest valuation for each licence. Under the rules of the UK auction only one licence can go to bidder 1. All other licences have to go to other bidders, and thus inevitably these licences are awarded to bidders who do *not* value them the most.

The simultaneous ascending auction does, however, achieve efficiency in another sense. It achieves an allocation of licences to bidders which (approximately) maximises the sum of valuations *subject to the constraint that each bidder can receive only one licence, and subject to the constraint that licence A has to go to an outsider.* We give in Appendix 2 a mathematical proof of this assertion. The assertion and an informal proof are also contained in Binmore and Klemperer (2001). The result is closely related to Theorem 2 of Milgrom (2000). Milgrom's proof is built on the First Welfare Theorem of general equilibrium theory which shows that equilibria of competitive markets are efficient (see, for example, Mas-Colell, Whinston and Green (1995, p. 549)). Our proof is self-contained, but is in style very similar to the proof of the First Welfare Theorem. The proof thus highlights how auctions mimic competitive markets.

Related Literature

The most closely related paper is Plott and Salmon (2001). Plott and Salmon propose a theory of bidding in simultaneous ascending auctions which is essentially equivalent to our assumptions of private values and straightforward bidding.[17] They give a stochastic formulation of this theory, and test it on experimental data where they find that the theory performs well. In a second step they apply the theory to the same data which we also investigate in this paper. They find that the estimates which they obtain are of some limited help in understanding the data.

In particular, Plott and Salmon find that their estimates of different companies' values explain these companies' bids to a degree which varies a lot from company to company. For example, their estimates of NTL Mobile's values rationalize only 43% of that company's bids. Their estimates of Worldcom's values, by contrast, explain 87% of that company's bids. Our work provides more detailed insights into individual companies' bidding behaviour, and thus a better understanding of why the percentages found by Plott and Salmon vary from company to company. In those cases in which the private value/straightforward bidding model is not very successful at explaining a company's behaviour our work also provides more insight than Plott and Salmon's into the precise way in which the observations deviate from the model. As indicated above, we find very specific and systematic deviations and not just random fluctuations.

Plott and Salmon also investigate the extent to which estimates based on the first 75 or 100 rounds allow an outside observer to predict the final licence winner and the price which they will pay. They find that these predictions are reasonably accurate. Our investigation below shows that any efforts to predict on the basis of the first 75 or 100 rounds not just the final winners, but also the bids placed in the intervening rounds (101 to 150) would lead to very inaccurate forecasts for some companies.

The different focuses of the two papers explains why the general tenor is different. Whereas Plott and Salmon are, in general, positive about the empirical success of the private value/straightforward bidding model, we are more skeptical. As the data which they and we investigate are limited no conclusions can be drawn with certainty from either analysis.

[17] Plott and Salmon make additional assumptions about bidders' private values (see Plott and Salmon's equation (3)) whereas we do not make any such assumptions.

There is also some empirical literature about the spectrum auctions in the United States. Cramton (1997) is a review of a variety of FCC auctions. Cramton (1995) analyses the nationwide narrowband PCS auction. The main difference between this auction and the UK auction is that in the US auction each bidder could acquire up to three licences. Ausubel et. al. (1997) are concerned with the broadband PCS auctions for licences A,B and C. These licences were regionalized licences, unlike in the UK auction where licences were nationwide. Ausubel et. al. investigate the bidding data for evidence of geographic synergies. Cramton and Schwartz (2000a,b) give evidence of collusion through bid signaling in the broadband PCS auctions for licences D, E and F. The main purpose of this collusion was to achieve coordination among bidders about how to divide the available licences among themselves. It is crucial to the signaling techniques which Cramton and Schwartz describe that bidders could bid simultaneously on more than one licence.

3 Empirical Analysis

We proceed in three steps. First, we ask how bidders chose for which licence to bid. Then we ask how bidders chose how much to bid. Finally, we ask how bidders chose when to withdraw from the auction.

Most of our attention will be focused on the first step. In this step we shall not take account of what companies actually bid, as this is the subject of the second step, but instead we shall ask which licences they chose to place a bid on, as a function of the minimum admissible bid for that licence. We shall refer to that bid from now on as "the price" of that licence.[18]

The first step will be divided into three parts. First we ask how bidders, in rounds in which they chose to bid for one of licences A or B, chose whether to bid for A or for B. Second, we ask how bidders, if they chose to bid for one of the licences C, D and E, chose which licence to bid for. Finally, we ask how bidders decided whether to bid for

[18]Note that our terminology thus deviates from that used by the Radiocommunications Agency. The Radiocommunications Agency called the currently leading bid the "current price". We think it more appropriate to call the amount required to overbid the currently leading bid the "price".

a "large" or a "small" licence. Note the conditional nature of the first two questions. In the first question, for example, we do *not* ask what it was that induced companies to bid for a large licence. We only ask which licence they chose to bid for *if* they had decided to bid for a large licence.[19]

Note that it is only the decision to withdraw which can reveal to an outside observer the absolute level of the value which a company attaches to a licence. However, companies' decision to bid for one licence rather than another reveals to the outsider information about the value differences among licences. It is these differences on which we shall focus below. To illustrate how differences are revealed consider, for example, the very first bid placed by BT3G in the auction. This bid was a bid for licence B. The minimum bid for licence B in the first round was £107.1 million. BT3G could also have bid for one of the small licence. All small licences had a minimum bid of £89.3 million. By bidding for licence B the company revealed that it valued the large licence B at least £(107.1-89.3) million = £17.8 million higher than the small licences. It is this type of information with which we shall work below.[20]

How Did Bidders Choose Whether to Bid for Licence A or for Licence B?

Recall that only the nine new entrants were allowed to bid for licence A, and thus our discussion can only concern these nine companies. Among these nine companies, two never bid for licences A or B (Epsilon and Crescent). Thus, we are left with seven companies whose decisions need to be investigated.

Licence A was larger than licence B. When choosing whether to bid for A or for B, companies had to compare the difference in their valuations of the two licences and the difference between the current minimum bids for licences A and B. We show in Figure 1 how this latter difference evolved over the 150 rounds of the auction. Figure 1 illustrates that in most rounds the difference between the minimum bids for A and B was negative, despite of the fact that licence A was bigger. In those rounds in which the difference was positive, it was relatively small. These facts reflect the more intense

[19] Of course, when asking this question, we shall not be concerned with incumbents as these could only bid for one of the large licences (licence B).

[20] The same idea is the key to Plott and Salmon's (2001) work.

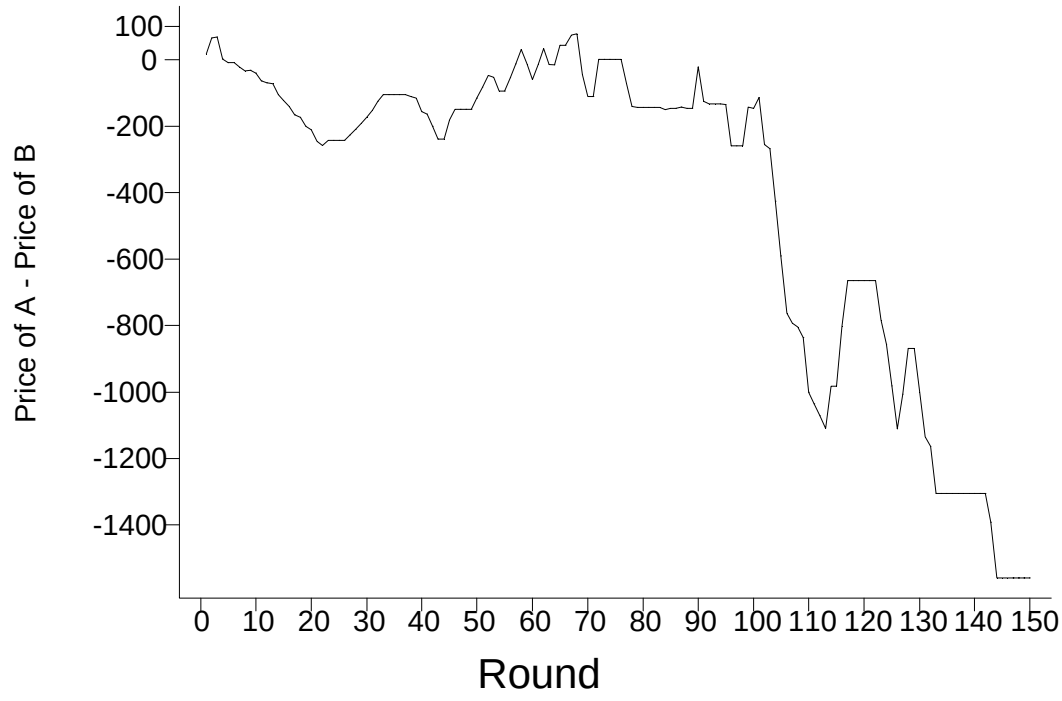

Figure 1: Price of A - Price of B (in £ millions)

competition for licence B which is due to the restriction that incumbents could bid only for B but not for A.

Under the assumptions of private values and straightforward bidding, companies which attached a significantly higher value to A than to B should never have bid for B. We do indeed find that among the seven companies which we consider four never bid for B, but placed bids on A only. These four are: NTL Mobile, Worldcom, One.Tel, 3GUK.

Now consider the three remaining companies: TIW, Telefonica, Spectrumco. If in a round one of these companies placed a bid on licence A then we can deduce that the difference between its valuations for A and B is larger than the difference between the price of A and the price of B in that round. This inference is most informative if we consider among all rounds in which the company bid for A that round in which the price difference is largest. In Table 3 we display for each of the three companies in question in the first column this maximum price difference between A and B which is still compatible with the company bidding for A. By considering the periods in which

the companies bid for licence B we can similarly deduce what is the smallest price difference which induced a company to bid for licence B. This is shown in the third column of the table. The difference between a company's value for A and for B must be between the value in the second and the value in the fourth column.

Company	Lower Bound	No. of Bids for A	Upper Bound	No. of Bids for B
TIW	£17.9 million	12	-£71.9 million	5
Telefonica	£17.9 million	6	£65.7 million	1
Spectrumco	-£8.6 million	21	£0.5 million	5

Table 3: Valuation of A-B (Upper and Lower Bounds)

For Telefonica, for example, we thus conclude that it regarded licence A as more valuable than licence B, and that the value difference was between £17.9 millions and £65.7 millions. For Spectrumco we cannot be sure whether it regarded licence A as more valuable than licence B, but we can certainly deduce that any value difference which Spectrumco perceived must have been extremely small.

We are left with one problematic case, that of TIW. Among all companies whose choices we are considering here this is the only company whose behaviour is not compatible with our hypothesis of private values and straightforward bidding. This is reflected in Table 3 by the fact that the entry in the second column is larger than the entry in the fourth column. Thus, there is no valuation difference which can rationalize TIW's bidding behaviour.

Although we thus find a violation of our basic hypothesis, it is relatively minor. If we neglect TIW's bidding behaviour in the first 13 rounds, then the problem disappears because in later rounds TIW never bid for licence B. We shall therefore in our further analysis of TIW's bidding behaviour neglect the first 13 periods, and treat TIW like those companies who only bid for A but nor for B.

How did bidders choose whether to bid for licence C, D, or E?

Licences C, D and E were from the perspective of an outsider almost identical. However, all licences corresponded to fixed frequencies of the spectrum, and bidders might

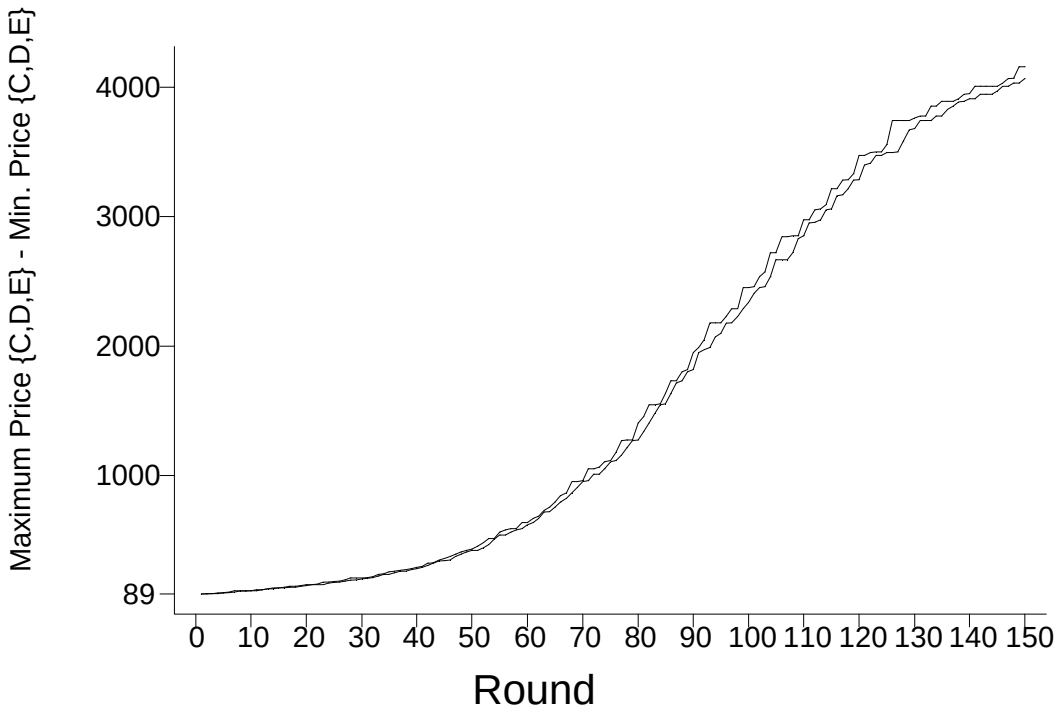

Figure 2: Maximum Price of C, D and E - Minimum Price of C, D and E (in £ millions)

have had preferences for particular frequencies, for example for networking reasons. Also, some frequencies were next to guard bands whereas others were not.

Under our assumptions of private values and straightforward bidding, if companies were indifferent between licences C, D and E, they should always bid for the licence which currently had the lowest price. In the following we investigate whether this was indeed how companies placed their bids, or how they deviated from this rule.

To begin with we show in Figure 2 how the lowest and the highest price of any of the licences C, D and E evolved during the auction. Figure 2 illustrates that these prices, and therefore the prices of all three licences, stayed very close together for the complete duration of the auction. There was therefore no possibility to observe large and substantial deviations from the predictions of our baseline assumptions.

Among the thirteen companies one, Vodafone, never placed a bid on licences C, D or E. Four others, BT3G, One.Tel, Spectrumco, and Crescent always bid for the cheapest of these three licences. These companies' behaviour is thus compatible with

our baseline assumptions and the hypothesis that licences C, D and E were identical.

Two others, One2One and Worldcom, deviated so rarely from the baseline assumption that we regard these deviations as insignificant. One2One placed 105 bids during the auction on one of licences C, D and E. Only one of these 105 bids deviated from the rule that One2One would only bid for the cheapest of these licences. This was their bid in round 76 for licence E whose price in that round was £1,181.3 million. In that round licence C cost only £1,117.4 million. One2One placed a bid of £1,212.1 million on licence E. Note that the bid if read aloud reflects the company's name. This suggests some unusual motive for this bid. If one takes the price which One2One ultimately paid for licence D, i.e. £4,003.6 million, to be a lower boundary for their evaluation of any of the smaller licences, then the potential surplus loss due to this bid is at most 2.2%. This seems to be a significant amount. But as this was only one out of 105 bids, and because of its strange nature, we shall ignore it, and assume that One2One regarded licences C, D and E as identical. In our further exploration we shall thus ignore round 76 when considering One2One's bidding behaviour.

Only two out of 57 bids of Worldcom for licences C, D and E were not for the cheapest of these licences. Worldcom withdrew in round 121 when the cheapest of licences C, D and E was worth £3,281 million Pounds. If we take that to be Worldcom's evaluation of these licences, then the percentage of foregone surplus in their two deviating bids is 0.38 % (round 70) and 0.46 % (round 84). Because these percentages are so low we shall assume in the following that also Worldcom regarded licences C, D and E as identical.

Next there are five companies who regularly deviated from the rule of bidding for the cheapest of licences C, D and E. These are TIW, NTLMobile, Telefonica, Epsilon and 3GUK. Moreover, for none of these companies is there any set of valuation differences which would rationalize their behaviour. We have therefore estimated these companies' valuation differences allowing for the possibility that occasionally a random bid is placed which does not reflect the estimated valuation differences.

The estimated valuation differences are displayed in Table 4. These estimates were obtained as maximum likelihood estimates in a conditional multinomial logit (random utility) model in the style of McFadden (1974). We explain in Appendix 3 the model

in more detail. The estimated Standard Deviation which we report in Table 4 refers to the random disturbance of bidders' valuation of licences as postulated by McFadden's random utility model.

Bidder	Value C-E	Std Error	Value D-E	Std Error	Standard Deviation	Std Error
TIW	-6.9	5.0	-3.8	5.0	13.5	3.7
NTL	16.6	9.7	15.5	9.6	18.0	7.0
Telefonica	16.7	15.4	31.5	17.9	33.6	11.7
Epsilon	1.7	4.4	-0.2	4.4	11.6	3.2
3G UK	1.3	2.4	0.7	2.4	6.9	1.8

Table 4: Estimated Value Differences (in £ millions)

Table 4 shows that none of the estimated value differences is significantly different from zero if we set the significance level to 5%. We find it most plausible to conclude that it is not value differences but other considerations which drives these companies' bidding behaviour. For example, the bidding that we observe may be analogous to jump bidding. As we explain later there was a significant amount of jump bidding in this auction where bidders bid more than the minimum bid. We mentioned in Section 2 that jump bidding may have been rational in this auction. Just as jump bidding might have been rational, it might also have been rational to bid for, say, the second cheapest licence among C, D and E, instead of bidding for the cheapest of these licences.

The company whose bidding behaviour deviated strongest from the homogeneity hypothesis was Orange. Orange only bid for licence E. It never bid for licences C or D. Thus, Orange's behaviour is compatible with our basic hypothesis of private values and straightforward bidding, provided that these assumptions are combined with the somewhat unexpected evaluation that licence E was much more valuable than licences C and D, and that the difference in value was in each round at least as large as the difference between the price of E and the prices of C or D.

How Did Bidders Choose Whether to Bid for a Large or a Small Licence?

Having described how bidders chose among large licences, and among small licences, we now turn to bidders' choice between large and small licences. It is at this point that we find the most significant deviations from our hypothesis of private values and straightforward bidding. Several important bidders' behaviour is incompatible with this hypothesis. They deviate from the hypotheses in a robust and persistent manner. Inconsistencies occur not only in the initial phases of the auction but throughout the auction, and even at times at which the stakes are very high indeed.

We shall divide bidders into four groups and discuss the behaviour of bidders in these four groups in turn. The first group consists of the incumbents, all of whom won a licence. The second group consists of just one firm, the outsider TIW who won licence A. The third group consists of three firms, NTL Mobile, Telefonica and Worldcom, who participated in the auction beyond round 100. The fourth group consists of all remaining firms, i.e. the outsiders who dropped out between rounds 94 and 100.

Incumbents: Three of the four incumbents picked the licence on which they bid in accordance with our basic hypotheses. However, one company's behaviour deviated strongly. The three incumbents whose behaviour accords with our hypothesis are Vodafone, Orange, and One2One. The one incumbent whose behaviour deviates strongly is that of BT3G.

Vodafone only bid for licence B. They never bid for any other licence. Thus, their behaviour could reflect that the additional value which they attached to licence B in comparison to all other licences was always larger than any price difference between licence B and the other licences. One2One never bid for licence B. Moreover, among C, D and E, as explained above, they only once deviated from the rule of bidding for the currently cheapest licence. Thus, their behaviour roughly indicates that the price difference never made it worthwhile for them to bid for B, and that they regarded licences C, D and E as identical.

Orange and BT3G switched back and forth between a small and a large licence. Orange's behaviour was approximately consistent with the view that they estimated that the value of a large licence exceeded that of a small licence by about £400 million. Some bids deviated from this rule, but the deviations were small. By contrast, British Telecom's bidding is not even approximately consistent with any fixed estimate of the

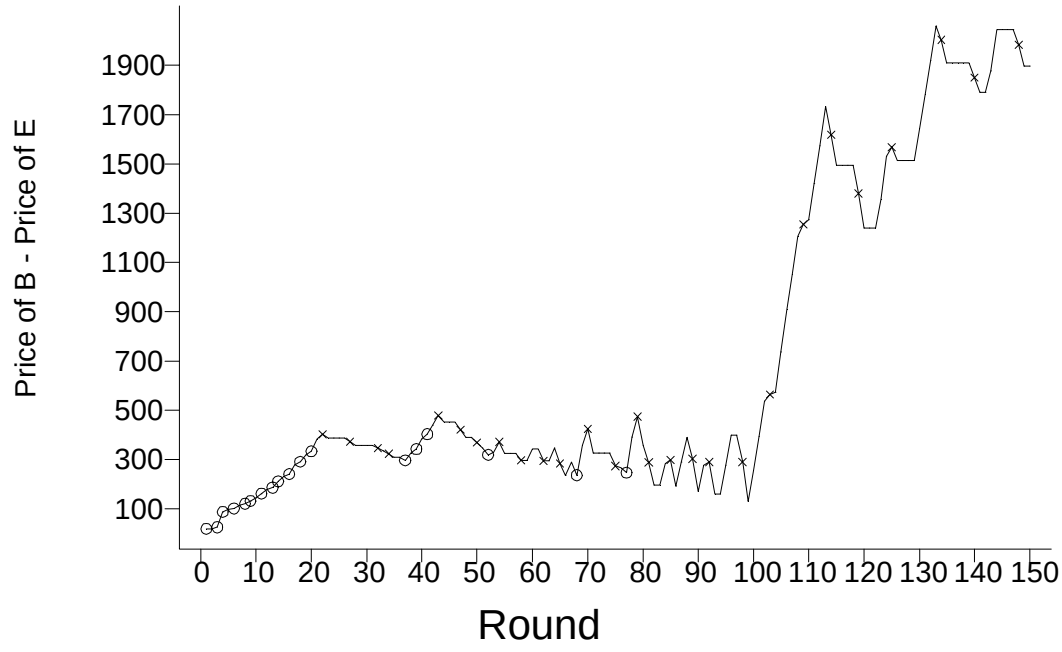

Figure 3: Orange's Bids for Large and Small Licences (Bids for Small Licences: x; Bids for Large Licences: o)

difference between the value of a big and of a small licence.

We illustrate the difference between the behaviour of Orange and that of BT3G in Figures 3 and 4. Both figures show a curve indicating the difference between the price of a big and the price of a small licence (in £ millions) in each round of the auction. The figures are adjusted to individual firm's behaviour in the following way. For Orange, the price of a small licence is always the price of licence E, because Orange never bid for any of the other small licences. For BT3G the price of a small licence is always taken to be the minimum of the prices of C, D and E, because BT3G always bid for the cheapest of these licences. For both companies, the price of a large licence is the price of licence B.

In each figure those rounds in which a company bid for a small licence are marked with a cross, and we mark rounds in which a company bid for a large licence with a circle. Bidding is consistent with our hypothesis of fixed private values and straightforward bidding if it is possible to draw a horizontal line through the figure which

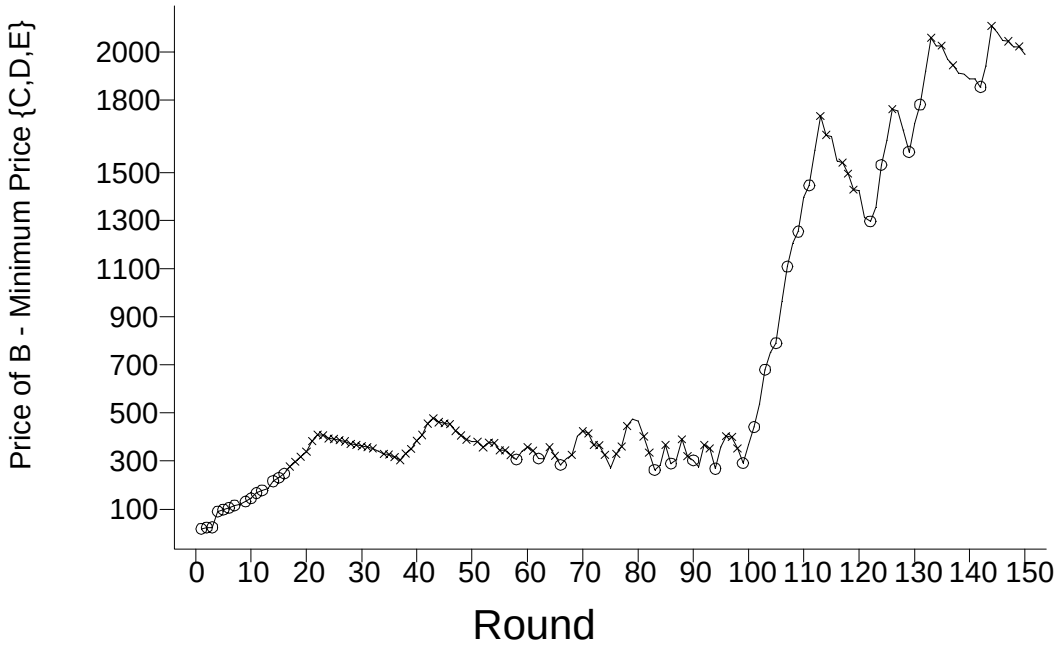

Figure 4: BT3G's Bids for Large and Small Licences (Bids for Small Licences: x; Bids for Large Licences: o)

separates the circles from the stars so that all the circles lie below the horizontal line and all the stars lie above the horizontal line. The intersection of the horizontal line with the y-axis indicates then a firm's evaluation of the value difference between a big and a small licence.

In Figure 3 such a separating line can be drawn for Orange at around £300 millions. In Figure 4, however, for BT3G no such separating line exists because BT3G keeps alternating between big and small licences as the price difference goes up.

Note that the inconsistency of BT3G's bids with our basic hypothesis is *not* primarily a phenomenon that concerns the beginning of the auction. In fact, BT3G's initial behaviour is compatible with the hypothesis that their estimate of the value difference between a big and a small licence is slightly smaller than that of Orange, perhaps around £300 million. From round 99 onwards there was a stark change in their behaviour, and they started to bid aggressively on a large licence. They were willing to bid on a large licence even though the price difference was now much larger

than £300 million. Indeed, the price difference soon exceeded $1,000 million. In fact, in round 142 BT3G was willing to bid for licence B even though at that stage the price difference between B and the cheapest small licence had gone up to £1,854.6 million.

One might think that from round 99 onwards BT3G had simply a higher evaluation of the difference between licence B and a small licence. However, BT3G's bidding even in the last 50 rounds of the auction does not consistently reveal a new evaluation of this difference. For example, in round 117 when the price difference was £1,541.2 million BT3G bid for a small licence whereas, as mentioned above, in round 142, when the price difference was £1,854.6 million, BT3G bid for a large licence.

It seems clear that BT3G's bidding behaviour was driven by considerations other than an evaluation of the difference between large and small licences. We shall speculate below which considerations this might have been, but we should confess right away that we have no completely convincing explanation.

TIW: TIW's bidding, like BT3G's bidding, deviates substantially from our hypothesis of private values and straightforward bidding. Figure 5 represents a similar graph for TIW as we have presented above for Orange and BT3G. For TIW we take licence A to be the large licence. As explained above we ignore TIW's initial bids for licence B. The price of a small licence is taken to be the minimum of the prices of licences C, D and E because we found above that TIW's evaluation of the differences between these licences was not significantly different from zero.

Figure 5 shows some parallels with the bidding behaviour of BT3G. Initial bids seem to reflect a relatively low estimate of the value difference between big and small licences. After the somewhat erratic bidding in the first 13 rounds of the auction, until round 100 TIW only bid twice again for licence A, and these two bids were placed when the price differences between licence A and the other licences was relatively low (£176.2 million in round 29 and £92.8 million in round 98). Later, TIW was willing to bid for a licence A when it cost £745.4 million more than the cheapest small licence (round 116). At the close of the auction TIW ended up paying for licence A £381.1 million more than was the price of the cheapest small licence.

Outsiders who participated beyond round 100: None of the three companies

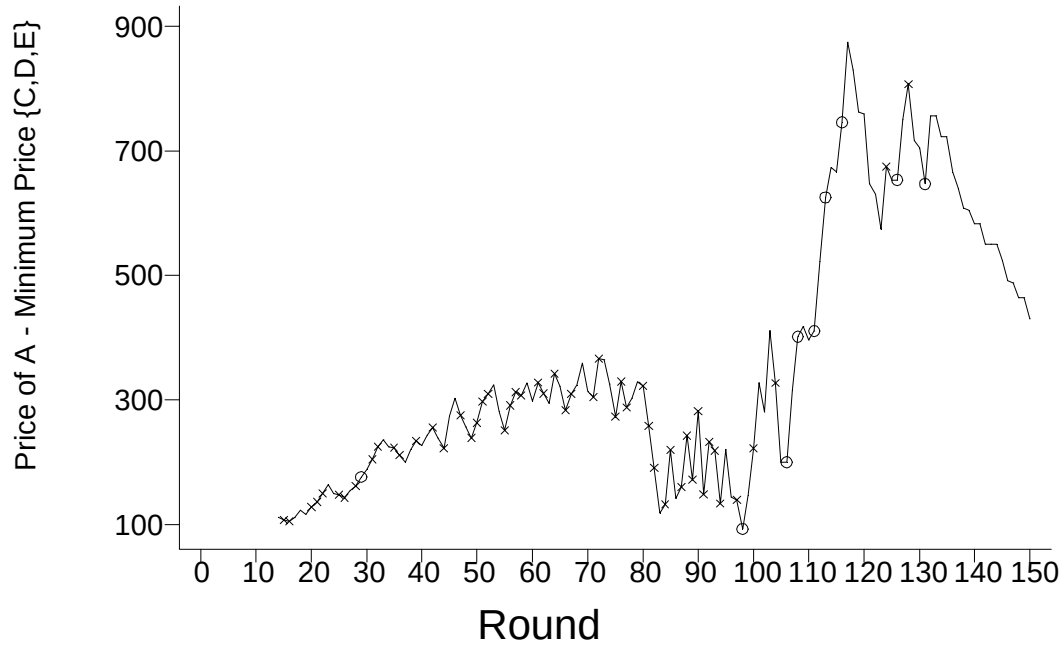

Figure 5: TIW's Bids For Large And Small Licences (Bids for Small Licences: x; Bids for Large Licences: o)

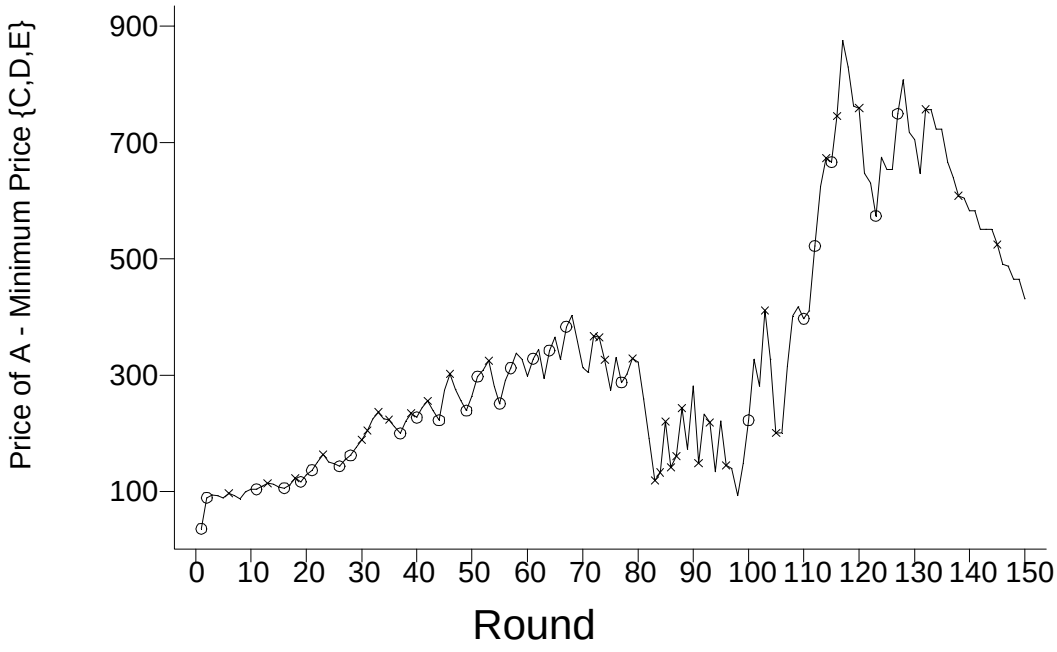

Figure 6: NTL Mobile's Bids For Large and Small Licences (Bids for Small Licences: x; Bids for Large Licences: o)

in this category, NTL Mobile, Telefonica, and Worldcom, bid in accordance with our hypothesis. We observe the most severe deviation from this hypothesis in the bids placed by NTL Mobile, the company whose decision to quit the auction in round 150 triggered the close of the auction. The other two companies in this group, Telefonica and Worldcom placed in comparison to NTL Mobile relatively few bids on a large licence. Telefonica bid only seven times for a large licence and Worldcom bid only five times for a large licence. By contrast, NTL Mobile bid 25 times for a large licence.

Figure 6 illustrates NTL Mobile's bidding. Recall that NTL Mobile never bid on licence B, and that we found the estimated value differences between licences C, D and E for NTL Mobile not to be significantly different from zero. Therefore, our figure displays the price difference between licence A and the cheapest of licences C, D and E.

Figure 6 suggests that NTL Mobile's estimate of the additional value of a large licence increased in the first approximately 70 rounds of the auction. In this period it

frequently switched between bidding for a large and a small licence, and it was willing to return to the large licence even if the price difference had increased. In rounds 70 until 100 NTL Mobile's bidding became much more cautious, and NTL Mobile abstained from bidding for a large licence even though the price difference had dropped. After round 100, however, NTL Mobile started again to place bids on large licences even though the price difference now became very large.

Outsiders who quit the auction between rounds 94 and 100: Most of the five companies in this group placed no or very few bids on a large licence. In particular, Epsilon and Crescent never bid for a large licence. One.Tel placed only two bids on a large licence, and 3G UK placed only four bids on a large licence. We focus on Spectrumco who bid more actively for a large licence, and whose behaviour we show in Figure 7. Recall that we have found earlier that Spectrumco's estimate of value differences between licences A and B must have been minimal, and that among the small licences C, D and E Spectrumco always bid for the cheapest. Therefore Figure 7 displays the difference between the lowest price of a large licence (A or B) and the lowest price of a small licence (C, D or E).

Figure 7 shows that Spectrumco's bidding was incompatible with the hypothesis of private values and straightforward bidding. Interestingly, it seems that Spectrumco's estimate of the extra value provided by a large licence dropped during the auction. Up to round 56 Spectrumco bid only for a large licence and it was willing to pay up to £310 million more for a large licence. However, in some later rounds Spectrumco refused to bid on a large licence although the price difference had become much smaller. For example, in round 86 the price difference between the cheapest large and the cheapest small licence was only £142 million, and Spectrumco decided to bid for a small licence.

How Did Bidders Choose How Much to Bid?

The large majority of bids in this auction were exactly equal to the lowest admissible bid, as postulated by our hypothesis of straightforward bidding. However, there were also a significant number of bids above the minimum bids ("jump bids"). Table 5 shows for different phases of the auction the distribution of the percentage amount by which bids exceeded the minimum bids. Table 5 covers all bids, i.e. bids which,

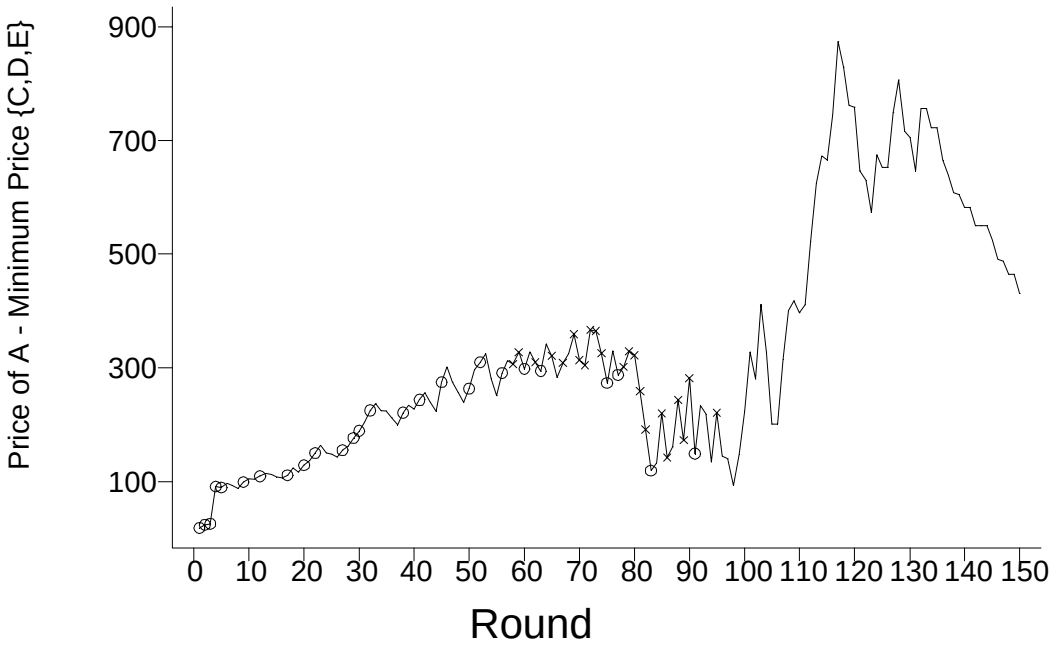

Figure 7: Spectrumco's Bids for Large and Small Licences (Bids for Small Licences: x; Bids for Large Licences: o)

when placed, were the largest bids for that licence, but also bids for which this was not true. The first row of Table 5 reflects the initial phase of the auction in which bids for most licences were below a quarter of the final winning bids for these licences. Because initially bids rose quite slowly the first row of Table 5 covers more rounds than the other rows. The bottom row of Table 5 refers to a relatively large number of rounds because otherwise the number of bids covered by the row would be quite small. In the last rounds of the auction only few bids per round were placed. The columns of Table 5 correspond to the amount by which a bid exceeded the currently admissible minimum bid for a licence, as expressed in percentages of the minimum bid. Each entry in Table 5 reflects the number of bids in that particular category, expressed as a percentage of all bids in the same row.

Rounds	0%	<1% jump bidding	1-2%	2-3%	3-4%	4-5%	>5%
1-70	76.0%	13.4%	3.0%	2.1%	2.5%	2.1%	0.9%
71-90	80.0%	11.3%	2.5%	1.3%	3.1%	0.6%	1.3%
91-110	80.0%	12.0%	6.7%	1.3%	0.0%	0.0%	0.0%
111-150	70.4%	24.0%	4.2%	1.4%	0.0%	0.0%	0.0%

Table 5: Distribution of Jump Bid Sizes

We explained in Section 2 that one possible rationale for jump bidding might be that bidders tried to increase their chances of obtaining a licence at prices close to current prices in case the auction closed very soon. An alternative view of jump bids might be that bidders tried to speed up the auction because they knew that the initial minimum bids were far below the prices that would ultimately have to be paid for the licences.

Now one would expect jump bids which are intended to speed up the auction to be larger than jump bids which are intended to break ties. On that basis Table 5 seems to indicate that the second interpretation of jump bids applies to early rounds, and that the first interpretation of jump bids applies to later rounds. Jump bids in the early rounds were larger than in the later rounds. This is intuitive because in early rounds the need to speed up the auction was perhaps transparent to many bidders. On the other hand, towards the end of the auction avoiding ties probably became a more important

motivation. All this is speculative, though. A Kolmogorov-Smirnoff test indicates that the distribution in the different rows of Table 5 do not differ significantly (using a significance level of 5%) from each other.

An interesting detail is that Vodafone who only bid for licence B never placed a jump bid, except in round 143, when they bid 1.3% more for licence B than was required. It was this bid which clinched licence B for Vodafone.

How Did Bidders Choose When to Drop Out of the Auction?

We indicated already in Tables 1 and 2 which bidders persisted until the end of the auction and therefore won a licence, and which bidders withdrew during the auction and therefore did not win a licence. Table 2 also shows in which rounds bidders withdrew. The most striking feature of these data is that there are five bidders whose withdrawal points are extremely close to each other: rounds 94 - 100.

Figure 8 presents an alternative way of looking at the withdrawals. We indicate the number of bidders left in the auction as a function not of the auction round but of the currently lowest admissible bid (in £ millions). The figure shows that the large number of withdrawals occurred when the minimum admissible bids had reached around £2,000 million, i.e. about one half of the lowest winning bid.

The fact that so many bidders' withdrawal points are so close to each other can be explained in several ways. One possibility is that informational considerations played a role, and that the first withdrawal (by Crescent in round 94) led other firms' to revise their estimate of the value of the licences in a way which made it also for them no longer worthwhile to stay in the auction. An interesting question is then why other bidders, including other outsiders, continued to bid in the auction.

Another possibility could be that these withdrawals were dictated by budget constraints i.e. that these five firms withdrew when they ran out of funds to pay for their bids.[21] The reason why these firms' budget constraints were so similar to each other might have been that there was a predominant view among investors about the value of the licences. An interesting question is then why investors evaluated licences so differently from those bidders who continued to bid in the auction.

[21] See also our comments on financial externalities in Section 4.

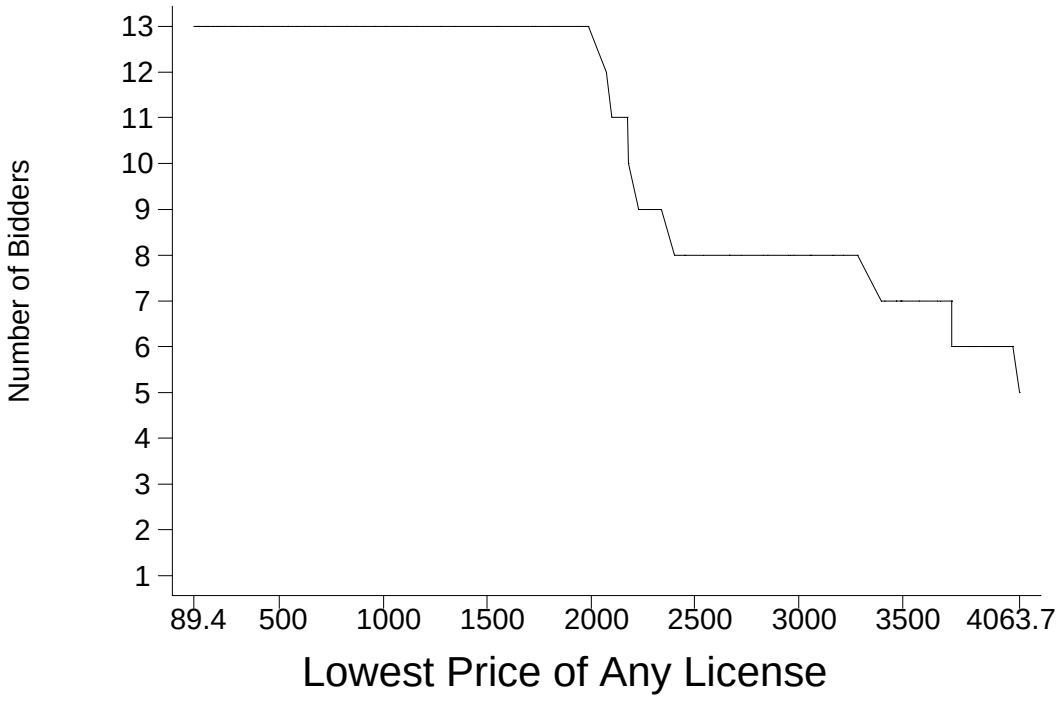

Figure 8: Number of Bidders

4 Discussion

In the previous section we have seen that the most important discrepancy between our basic hypotheses of private values and straightforward bidding and the actual bidding behaviour concerns the way in which bidders chose whether to bid for a large or a small licence. In this section we discuss alternative rationalizations of this aspect of bidders' behaviour. The discussion in this section is tentative. No firm conclusions can be reached. Auction theory does not offer us well-understood models in which the arguments which we consider below are formalized. As a consequence there is no clear way of checking whether the data support these arguments.

Information Effects

The apparent changes in companies' evaluation of the difference between a big and a small licence could be due to information which the companies acquired during the auction. There is no indication that information which could have had such an effect became publicly available through the media during the auction. However, companies'

private research might have been a source for such information. Another source might be other companies' bidding behaviour. If contrary to our private value hypothesis companies believed that other companies held private information relevant to their own evaluation then they might have tried to infer that information from the observed bidding of other companies. Moreover, if such inferences played a role during the auction, companies might have tried to manipulate other companies' beliefs, for example to induce them to bid on other licences.[22]

It is plausible that some such process of drawing inferences and signaling information has taken place during the auction. However, it is difficult to believe that these effects were the main source of the phenomena which we found in the previous section. This is because of the size of these phenomena. Recall that in the case of BT3G, for example, we found that their initial estimate of the value difference between a big and a small licence was about £300 million, but that later they were willing to bid for a large licence when the price difference had gone up to £1,854.6 million. Thus their estimate of the value difference seems to have multiplied by a factor of six. It is difficult to see which information BT3G might have acquired during the auction which could have lead to such a large change. It is also hard to believe that BT3G placed bids at such high stakes to send signals to its competitors, such as Vodafone. The situation is similar in the case of TIW, NTL Mobile and Spectrumco.

Allocative Externalities

The private value assumption implies that a company's valuation of a licence is independent of which other companies receive a licence. In practice, this might matter to companies. For example, incumbents in the UK market might have preferred other licences to be bought by outsiders rather than by incumbents, because outsiders might have been regarded as the weaker competitors. If such effects played a role

[22] The idea that different bidders might hold information privately which would be relevant for all bidders' valuations was raised during the preparation of the auction. In particular, the most prominent (although not the only possible) defense of the "Anglo-Dutch" auction which was for a while the favoured auction scheme (Binmore and Klemperer (2001)) has been based on the view that the information structure is that of an "almost common value auction" (Klemperer (1998)). This expression refers to a situation of the type described here.

then companies' evaluation of licences might have changed during the auction because their anticipation about who else would acquire a licence might have changed. Moreover, companies might have placed bids in order to manipulate which other companies received a licence.[23]

It seems to us, however, not plausible that such considerations explain the effects which we observed in Section 3. If the effects referred to in the previous paragraph were crucial, and if companies were straightforward bidders[24] who take as given the current allocation of licences (except, of course, the allocation of that licence on which they wish to place a bid), then the apparent changes in companies' valuations which we found in Section 3 should be related to the identity of the leading bidders on the other licences. We have so far not noticed any such connection. A more detailed and thorough investigation of this issue is left for future work.

Financial Externalities

Companies might not only have been concerned about which other companies acquire a licence, they may also have been concerned about the price at which other companies acquired such licences.[25] One would expect such a concern to be present if budget constraints play a role. In the context of this auction it seems likely that budget constraints were indeed important. There are two reasons why companies might have been concerned about other companies' financial position. The first is that competitors' financial position might influence their ability to finance the investment necessary

[23] Jehiel and Moldovanu (2000) and (2001) have suggested that such externalities were important in the European spectrum auction. However, their focus is on explaining the final outcomes of the European UMTS auctions, and not on the detailed bidding patterns. As far as the UK auction is concerned, their prediction regarding the outcome of the auction is that the four incumbents acquire a licence, as was indeed the case.

[24] Note that in this context there are no strong reasons to believe that straightforward bidding is an equilibrium strategy. However, as equilibrium strategies in auctions with allocative externalities are largely unkown there is also no strong reason to believe that bidders would employ equilibrium strategies.

[25] The possible importance of financial externalities in the European UMTS auctions was emphasized by Maasland and Onderstal (2001). They develop a theory of equilibrium bidding with financial externalities in the case that only one licence is sold.

to develop a third generation mobile phone network in the UK. The second reason is that competitors' financial position might influence their ability to bid in the European spectrum auctions which followed the UK's auction. Both considerations would give companies an incentive to raise the price which competitors' have to pay.

BT3G's bids for licence B might have been driven by such considerations. BT3G might have been convinced that Vodafone was determined to acquire licence B even if they had to pay a price far higher than ever reached in the auction. Vodafone never bid for any other licence, and it overbid immediately each other bid that was placed on licence B. BT3G might therefore have believed that it could place bids on licence B without any risk of ever having to pay for those bids, and that it could raise in this way the price which Vodafone had to pay for its licence.

Although this is an interesting speculation, we are not convinced by it. Vodafone was probably the financially strongest company participating in the UK auction. If financial externalities played a role, then one would expect that the financially weakest companies were pushed by their competitors to pay higher prices. We have not found clear evidence of this in the UK data, but we postpone a systematic investigation of this to future work.

Management Disagreements

Some companies' behaviour, for example that of British Telecom or TIW, could be viewed as a change of strategy during the auction. For example, one could argue that British Telecom and TIW's more aggressive bidding for a large licence from round 100 onwards indicated that a different group of managers had won control over the bids placed by the company. We have no direct evidence to support this suggestion.

Some comments by Sir Christopher Bland, who was appointed as new chairman of British Telecom in April 2001, are interesting in this context. A few days after his appointment he indicated in an interview with the "Independent on Sunday" that in his opinion the company "should never have bid for a third-generation telephone licence" (Independent on Sunday, 2001). The "Independent on Sunday" added: "However, he is not critical of BT's board for bidding for a licence: 'Hindsight is a wonderful thing'." (Independent on Sunday, 2001). Despite of the last sentence one might view these

comments as an indication that also at the time of the auction leading managers in the industry need not all have held the same view about how to bid in the auction. Thus, these comments lend some indirect support to the hypothesis that management disagreements may have played a role.

Conclusions

This paper has identified systematic and important deviations of bidders' behaviour in the United Kingdom's third generation spectrum auction from theoretical predictions. The theoretical framework which we tested is the only one for which it is known that simultaneous ascending auctions will lead to efficient outcomes. It is also the framework on which significant pieces of the advice offered to the UK government were based. Our analysis suggests that we understand less well than previously thought how and why simultaneous ascending spectrum auctions work.

5 Appendix 1: Equilibrium

In this appendix we sketch an argument which shows that straightforward bidding is an equilibrium under the private value assumption. Our sketch is informal and we have not checked all details. A complete proof is left to future work. Our proof sketch will also bypass the issue of jump bidding. A formal proof would have to be based on a framework in which this issue cannot arise, for example a framework in which prices rise continuously rather than in discrete steps.

We need to show that under the private value assumption no bidder can gain by deviating from straightforward bidding provided that all other bidders bid straightforwardly. In principle there are very many conceivable deviations from straightforward bidding which would need to be investigated. In particular, one would have to consider alternative strategies which are in potentially complicated ways history-dependent. However, a general result in game theory called the "one deviation principle" [26] suggests that we can simplify this task, and that it is sufficient to consider the case that a bidder deviates from straightforward bidding in a single round only, and that this bidder returns to straightforward bidding in all subsequent rounds.

Thus suppose bidding has reached some particular round, and that a bidder considers to deviate from straightforward bidding in this round only. To assess the consequences of such a deviation the bidder will need to consider two cases. Firstly, the case in which the auction would close in the current round if the bidder were to bid straightforwardly, and secondly the case in which the auction would not close in the current round if the bidder were to bid straightforwardly. In the first case straightforward bidding is the optimal strategy if one ignores the possibility of ties.[27] Straightforward bidding would guarantee that the bidder gets his most desired outcome at the current prices. Any deviation would raise prices, and thus no utility improvement is conceivable for this bidder.

Now suppose that under straightforward bidding the auction would not close in the current period. We shall argue that also in that case a deviation will not improve

[26] Lemma 98.2 in Osborne and Rubinstein (1994).

[27] It is at this point that we bypass the issue of jump bidding. As discussed in Section 2, once the possibilities of ties is taken into account, jump bidding might be an optimal way of avoiding ties.

utility. Consider first that the deviation considered is to withdraw and thereby close the auction. Then the deviation will lead to a utility of zero. Straightforward bidding can never lead to a utility which is lower than zero, and sometimes it will lead to a higher utility. Thus the deviation is not profitable.

Finally, suppose that the deviation which the bidder contemplates is to bid for some licence other than the licence that he should bid for under straightforward bidding. The consequence of this deviation cannot be that the auction closes. The only scenario under which this would be possible were one in which the deviating bid is placed on a licence for which no other bid has been received in the auction so far. But then the auction cannot close because bidders who don't currently have a licence would want to bid on the same licence as the deviating bidder before the auction closes. Thus, the deviating bid cannot cause the auction to close.

The deviation can thus only change the initial point for further rounds of straightforward bidding. However, such a change in the initial point will be outdone by future rounds of bidding. Licences which have experienced slower price rises become slightly more attractive and will receive larger bids.[28]

[28] A precise formalization of this last argument is one of the points in this Appendix which we leave to future work.

6 Appendix 2: Efficiency[29]

In this appendix we show that under the private value assumption straightforward bidding results in an approximately efficient allocation. The argument for this is simple, and therefore we can provide a complete formalization here.

First we need to introduce some notation. Denote by $L = \{\emptyset, A, B, C, D, E, \}$ the set of all licences where the empty set symbol $\emptyset$ stands for the case that a bidder gets no licence. Let $i = 1, 2, ..., 13$ be the bidders. For every licence $\ell \in L$ denote by $v_i(\ell)$ the value which bidder i attaches to licence ℓ. If $\ell = \emptyset$ we obviously have $v_i(\ell) = 0$.

The purpose of the auction is to achieve an allocation of licences to bidders. Let us denote such an allocation by λ. Thus, λ assigns to every i an element $\lambda(i)$ of L. We call an allocation λ admissible if there is exactly one i for whom $\lambda(i) = A$, analogous conditions hold for licences B, C, D and E, and the bidder i for whom $\lambda(i) = A$ holds is not an incumbent mobile operator.

For any licence ℓ and round n denote by $b(\ell, n)$ the bid of the leading bidder for licence ℓ in round n. Here, of course, we set $b(\emptyset, n) = 0$. Let $p(\ell, n)$ be the price of licence ℓ in round n, i.e. $p(\ell, n)$ is the minimum bid that a bidder who wants to bid for licence ℓ in round n has to make. We define here, of course, $p(\emptyset, n) = 0$. Let the last round of the auction under straightforward bidding be round N.

The assertion which we wish to prove here is that the allocation of licences at the end of the auction approximately maximises the sum of valuations. The sum of the valuations is:

$$\sum_{i=1}^{13} v(\lambda(i), i).$$

The amount by which maximisation may be missed is the sum of the minimum incre-

[29] The efficiency result with which this appendix deals is also mentioned in Binmore and Klemperer (2001) who, however, neglect in their statement of the result the effect of discrete minimum increments. The proof which we provide is more formal than the argument which Binmore and Klemperer give verbally on p.14 of their paper, and it accounts for minimum increments. The result and its proof are also closely related to Theorem 2 of Milgrom (2000). Milgrom considers the more complicated context in which bidders can buy more than one license. Whereas our proof is self-contained his proof invokes the First Welfare Theorem of general equilibrium theory.

ments in the last round:

$$\Delta = \sum_{\ell \in L} \left(p(\ell, N) - b(\ell, N) \right).$$

Our claim can thus be written as:

$$\sum_{i=1}^{13} v_i(\lambda(i)) + \Delta \geq \sum_{i=1}^{13} v_i(\lambda'(i))$$

for every admissible allocation λ'.

To prove this we first observe that Δ can also be written as:

$$\Delta = \sum_{i=1}^{13} \left(p(\lambda(i), N) - b(\lambda(i), N) \right).$$

Our assertion is thus equivalent to:

$$\sum_{i=1}^{13} v_i(\lambda(i), N) + \sum_{i=1}^{13} \left(p(\lambda(i), N) - b(\lambda(i), N) \right) \geq \sum_{i=1}^{13} v_i(\lambda'(i))$$

for every admissible allocation λ'.

Our proof is indirect. Suppose there were another allocation λ' which satisfies all conditions which λ satisfies, and for which the following holds:

$$\sum_{i=1}^{13} v_i(\lambda'(i)) > \sum_{i=1}^{13} v_i(\lambda(i)) + \sum_{i=1}^{13} \left(p(\lambda(i), N) - b(\lambda(i), N) \right).$$

Subtract on both sides of this inequality the sum of all prices in round N. Then one obtains:

$$\begin{aligned} \sum_{i=1}^{13} v_i(\lambda'(i)) - \sum_{i=1}^{13} p(\lambda'(i), N) &> \sum_{i=1}^{13} v_i(\lambda(i)) - \sum_{i=1}^{13} b(\lambda(i), N) \Leftrightarrow \\ \sum_{i=1}^{13} \left(v_i(\lambda'(i)) - p(\lambda'(i), N) \right) &> \sum_{i=1}^{13} \left(v_i(\lambda(i)) - b(\lambda(i), N) \right). \end{aligned}$$

The sum on the left hand side can be larger than the sum on the right hand side only if at least one of its summands is larger:

$$v_i(\lambda'(i)) - p(\lambda'(i), N) > v_i(\lambda(i)) - b(\lambda(i), N) \text{ for some bidder } i.$$

Consider that bidder i for whom this inequality holds. If i receives no licence at the end of the auction, i.e. $\lambda(i) = \emptyset$, then bidder i withdraws either in round N or in some

earlier round. By definition the right hand side of the above inequality is zero. Thus bidder i would have positive surplus from bidding for licence $\lambda'(i)$ at the end of the auction. But then he must have had positive surplus from bidding for licence $\lambda'(i)$ at the time at which he dropped out of the auction.[30] Thus we have a contradiction to our assumption of straightforward bidding.

If bidder i, however, does get a licence at the end of the auction, i.e. $\lambda(i) \in \{A, B, C, D, E\}$, then i has not withdrawn from the auction in round N. The right hand side of the above inequality then represents the surplus which bidder i expected in the round in which he placed his last bid on $\lambda(i)$. The larger left hand side of the inequality represents the surplus which bidder i could expect if he placed a bid on licence $\lambda'(i)$ in round N. At the time at which bidder i placed his last bid on $\lambda(i)$ the expected surplus from $\lambda'(i)$ must have been the same as in round N or larger. Thus, in that round straightforward bidding would have required bidder i to bid for licence $\lambda'(i)$. Thus we have obtained a contradiction with the assumption of straightforward bidding.

[30] Recall that by construction if i is an incumbent then $\lambda'(i) \neq A$, and hence i was entitled to bid for A.

7 Appendix 3: Estimating Value Differences

To estimate value differences among licences C, D and E we construct a random utility model of bidding in the spirit of McFadden (1974). We only consider rounds in which a bidder bids for one of these three licences, and we focus on the choice among these three licences, i.e. we ignore that the bidder might also have been able to choose licence A or B. We assume that bidder i's perceived utility from licence $\ell \in \{C, D, E\}$ in round n of the auction is a random variable:

$$u_i(\ell, n) = v_i(\ell) + a_i \varepsilon_i(\ell, n)$$

where all random variables $\varepsilon_i(\ell, n)$ are standardised extreme value distributed with expected value zero and with variance $\frac{\pi^2}{6}$, and where the random variables $\varepsilon_i(\ell, n)$ are all stochastically independent. The constant $a_i > 0$ measures the extent to which bidder i's perceived utility is subject to a random disturbance. The larger a_i the larger is the random disturbance of perceived utility. Let $p(\ell, n)$ denote the price, i.e. the minimal admissible bid, of licence ℓ in round n. We assume that bidder i bids in round n for that licence $\ell \in \{C, D, E\}$ that maximises $u_i(\ell, n) - p(\ell, n)$.

The probability that bidder i bids for licence $\widehat{\ell}$ in round n is then given by

$$\frac{e^{\frac{1}{a_i}(v_i(\widehat{\ell}) - p(\widehat{\ell}, n))}}{\sum_{\ell \in \{C,D,E\}} e^{\frac{1}{a_i}(v_i(\ell) - p(\ell, n))}}.$$

This can be re-written as:

$$\frac{e^{\frac{1}{a_i}(v_i(\widehat{\ell}) - v_i(E) - (p(\widehat{\ell}, n) - p(E, n)))}}{\sum_{\ell \in \{C,D,E\}} e^{\frac{1}{a_i}(v_i(\ell) - v_i(E) - (p(\ell, n) - p(E, n)))}}.$$

This makes clear that the likelihood depends only on value differences, and that we can therefore only estimate value differences. Here, we focus for each licence on the difference between its value and the value of licence E, i.e. we estimate $v_i(C) - v_i(E)$ and $v_i(D) - v_i(E)$.

We use maximum likelihood methods to estimate $v_i(C) - v_i(E)$, $v_i(D) - v_i(E)$ and a_i. We report in Table 4 the estimated value differences. Instead of reporting the estimate $\widehat{a}_i$ of a_i we report the implied estimated standard deviation of $\varepsilon_i(\ell, n)$ which is $\widehat{a}_i \frac{\pi}{\sqrt{6}}$.

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