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STRANGE BIDS: BIDDING BEHAVIOUR IN THE UNITED KINGDOM'S THIRD GENERATION SPECTRUM AUCTION*

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This article studies bidding behaviour in the auction of radio spectrum for third generation mobile telephone services which took place in the UK in the Spring of 2000. We show that several companies' bidding behaviour deviates strongly from straightforward bidding with private values. In particular some companies' evaluation of the added advantage of having a large licence rather than a small licence seemed to change dramatically during the auction. No compelling explanation of this phenomenon seems available at this stage. We conclude that it is less well understood than previously believed how spectrum auctions work.

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 different auction formats for the award of licences in the mobile telephone and other sectors. The purpose of this article is to contribute to the analysis of the available evidence. We shall focus on one particular auction: the UK's sale of licences for third generation mobile telephone services in March and April of the year 2000.

This auction was organised as a *simultaneous ascending auction*. The key features of a simultaneous ascending auction are that all related licences are sold simultaneously, there are multiple rounds, new bids can be made in each round, and the auction closes only when bidding on *all* licences has stopped.[1] The simultaneous ascending auction is currently the most popular auction format for the sale of spectrum licences (Cramton, 2002). It was originally developed by McAfee, Milgrom and Wilson for the sale of PCS (Personal Communications Services) licences by the US Federal Communications Commission (FCC) between 1994 and 1996[2] but has since been used in a variety of other auctions in

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

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

the US and other countries.[3] The popularity of simultaneous ascending auctions makes it particularly important to evaluate the available evidence regarding bidder behaviour in such auctions.

There are four reasons why, among the simultaneous ascending spectrum auctions which have been conducted so far, the UK's auction is particularly suitable as the subject of empirical research. First, 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' (Binmore and Klemperer, 2002). Second, the auction 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.[4] A third point is that the UK used the simultaneous ascending auction design in particularly simple circumstances: each bidder could acquire at most one licence. By contrast, in the PCS auctions in the US, bidders could acquire more than one licence. The background to this is that licences in the UK were nationwide, whereas in the US they covered only limited geographical areas. When bidders can acquire more than one licence, complications such as synergies among licences arise (Ausubel *et al.*, 1997). The ability to bid for multiple licences also makes certain collusive strategies possible, where competitors link their bidding behaviour for one licence with bids for some other licence (Cramton and Schwartz, 2000, 2002). Neither of these effects played a role in the UK auction. The fourth factor which makes the UK third generation spectrum auction interesting is that the licences which were sold were not identical, but differed in the amount of spectrum assigned to them. Much of our analysis focuses on the differences in values attached to large and small (in terms of spectrum) licences. The analysis would be impossible if the licences were identical.

We shall investigate bidding behaviour in the UK third generation spectrum auction in the light of auction theory. However, we should emphasise that the theory of simultaneous ascending auctions is very incomplete. Even for the simple set-up with nationwide licences which we have here, and even if we are willing to assume independent private values, there is no theorem which would give a complete description of the sequential equilibria of this auction. We shall by-pass this problem by investigating a simple hypothesis regarding bidders' behaviour: the hypothesis of 'straightforward bidding with private values'. This hypothesis underlies one of the leading articles about simultaneous ascending auctions (Milgrom, 2000). The hypothesis postulates that bidders enter the auction with fixed valuations, one for each licence, which do not change during the auction. Bidders do not make jump-bids, i.e. they always place the minimum admissible bid. Moreover, it is assumed that bidders always bid for the licence which offers the highest current surplus, i.e. for which the difference between the licence's value and the minimum admissible bid is highest. Bidders drop out once the maximum surplus is negative.

[3] See, for example, the reviews of a variety of recent spectrum auctions in Börgers and Dustmann (2003), Jehiel and Moldovanu (2001) and Klemperer (2002*a*).

[4] At the time of writing these data are still available at a webpage of the UK's Office of Communications (Ofcom): http://www.ofcom.org.uk/static/archive/spectrumauctions/3gindex.htm.

As well as providing a natural benchmark for our empirical work, straightforward bidding with private values is the only bidding theory for which the auction literature contains a proof that the outcome of a simultaneous, ascending licence auction is efficient. 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 of Milgrom (2000, Theorem 2). Milgrom's argument covers the more general case in which bidders can bid for more than one licence. Efficiency is of interest here because efficiency, not revenue maximisation, was the primary goal of the UK 's government in the auction.[5] We emphasise that deviations from straightforward bidding with private values do not imply inefficiency of the auction outcome; they only imply that, if efficiency was achieved, it was not for the general reasons known to auction theorists.

Another reason for focusing on this benchmark is that during the preparation period preceding the auction some of the advice which was offered to the UK's government and which was also revealed to the potential bidders was based on the benchmark hypothesis. 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, 1999).[6] 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. It is thus interesting to know that in the actual auction straightforward bidding with private values was violated.

The main part of this article describes systematic deviations from the benchmark hypothesis in the UK auction. The deviations which we find concern how bidders chose whether to bid for a large or a small licence. Bidders' (revealed) estimate of the difference in value between a large and a small licence increases dramatically during the auction. It is largely this escalation, and the precise form which it took, which caused the UK auction to achieve such remarkable revenues. Yet, the causes of this escalation are poorly understood. We shall discuss speculations of what might have caused them, but none of these speculations comes close to being compelling.

Among other papers about the UMTS auction in the UK, the paper that is most closely related to ours is Plott and Salmon (2004). We postpone discussion of this paper until Section 3. Bidding in the UK third generation spectrum auction has also been studied by Cramton (2001) in a report for the National Audit Office. Cramton writes that 'Most of the bidders pursued a strategy of bidding on the licence that represented the best value. Bidders thus switched from licence to

[5] See the statement by Telecommunications Minister Barbara Roche to the House of Commons on 18 May 1998 quoted in the official Information Memorandum for the auction (Radiocommunications Agency and N. M. Rothschild & Sons, 1999, p. 5).

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

licence as the prices changed. ... The pricing dynamics were predictable, although certainly not the absolute values of prices' (Cramton, 2001, p. 50). Cramton's report does not include a detailed discussion of empirical evidence. We argue that if one adopts the interpretation of 'bidding for best value' described in this article, then the evidence that bidders bid for best value is not very strong. The UK third generation spectrum auction is also reviewed in Binmore and Klemperer (2002). Their focus is on the preparation of the auction, not on the actual bidding in the auction. Cable *et al.* (2002) consider share price data and ask whether the stock market performance of winners and losers in the UK auction was substantially different. They show that this is not the case. Finally, this article has a companion paper, Börgers and Dustmann (2002*a*), in which we undertake more detailed case studies of selected companies' behaviour, and investigate several possible explanations for deviations of actual bidding behaviour from the benchmark hypothesis. We summarise some of the findings in Section 5, and refer the reader to the companion paper for details.

The remainder of this article is organised as follows. Section 1 briefly reviews the rules and the outcome of the UK auction. Section 2 discusses the benchmark hypothesis of straightforward bidding with private values. In Section 3 we describe aspects of bidding behaviour which do not deviate from the benchmark hypothesis, or which deviate from it in relatively minor ways. Section 4 then describes one respect in which bids deviate significantly from the benchmark hypothesis. Section 5 contains speculations about possible explanations of what we observe. Section 6 contains concluding remarks.

1. A Short Review of the UK Auction

The licences sold by the UK's government were licences to use radio spectrum to operate third generation mobile telephone networks. The licences on offer were often called UMTS licences. UMTS is the standard for third generation mobile telephone systems adopted by the European Community. The 'UMTS Forum', an organisation 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).

The sale of UMTS licences in the UK was conducted in the year 2000 by the 'Radiocommunications Agency', an agency of the UK government. The Radiocommunications Agency ceased to exist on 29 December 2003, and its duties were assumed by *Ofcom*, the 'Office of Communications'. The Radiocommunications Agency sold five licences, labelled A, B, C, D and E. Each licence entitles its owner to use a part of the spectrum that is identified in the licence. Spectrum can be 'paired' or unpaired. Paired spectrum provides separate frequencies for communication from the base station to the mobile telephone, and for communications from the mobile telephone to the base station. With unpaired spectrum the same frequency is used for both directions. Licence A consists of 2×15 MHz of paired spectrum and 5 MHz of unpaired spectrum. Licence B consisted of 2×15 MHz of paired spectrum. Licences C, D and E consisted of 2×10 MHz of paired spectrum

and 5 MHz of unpaired spectrum. The licences are valid 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.[7]

Licence A was reserved for a new entrant into the UK's mobile phone market. The incumbent four mobile telephone operators of the UK, who were not allowed to bid for A, 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%).[8]

The auction was organised in 'rounds'. In each round except the first each licence had a 'current price' and a 'current price bidder'. 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.
(3) They could withdraw from the auction. 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. 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 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 raise 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 the high interest rate of 8.65% was applied to calculate later installments.

[7] This paragraph and the next five paragraphs are based on Radiocommunications Agency and N. 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 (2002).

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

We now describe what actually happened. The four incumbents entered the auction whereby BT Cellnet participated as BT3G. In addition, nine outsiders joined: 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 ensure 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 lowered in several steps from the initial 5% to 1.5% at the end of the auction. 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. An interesting consequence of this rule occurred when in round 133, or earlier, a decision was made to lower minimum increments to 1.5%. In subsequent rounds bids were received for almost all licences, and therefore 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 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. Several points about Tables 1 and 2 are worth mentioning. Many withdrawals occurred between rounds 94 and 100. All incumbents won a licence. All small licences were sold at roughly the same price. The price of the large licence B was roughly 50% higher than the price of the small licences. Because licence B also offered 50% more MHz of paired spectrum than the small licences, the price per MHz paired spectrum was roughly the same for licence B and licences C, D and E. Finally, the largest licence A sold at a significantly smaller premium than licence B.

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

Table 1

Winners

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 2
Withdrawals

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

2. Some Theory

To analyse bidders' behaviour in the UK auction we shall compare it to the benchmark hypothesis of *straightforward bidding with private values*. This hypothesis is taken from Milgrom (2000). It is as follows:

- 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.
- In every round, every bidder which is allowed to bid compares his valuation of each licence to the minimum bid that is needed to overbid the currently leading bid for that licence, and then picks 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*.

Our motivation for choosing this particular benchmark was discussed in the Introduction. Although we do not intend to mount a strong defence of the benchmark assumption, we argue that it is not obviously inappropriate. Consider first the 'private value' part of the assumption. At the time of the UK auction there was large uncertainty about the value of UMTS licences. However, it seems 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 should be a valid approximation.

Consider next the 'straightforward bidding' part of the hypothesis. If indeed private values constitute a valid approximation of the situation in which the bidders found themselves, then straightforward bidding does appear a rational strategic choice. In particular, it appears to be a sequential equilibrium if all bidders bid straightforwardly. Earlier papers have established that it would be dominant to bid straightforwardly using the true private values if only strategies of the other bidders which are straightforward strategies for *some* private values are considered.[9]

[9] This follows from the results of Leonard (1983) and Demange *et al.* (1986).

If strategies other than strategies which are straightforward for some private values are allowed, then one can easily see that straightforward bidding is no longer dominant. For example, the other bidders might adopt arbitrary 'punishment strategies'. However, as long as all other players' bidding strategies are straightforward for some private values, we conjecture that it remains optimal to bid straightforwardly as well.[10] A formal proof of this is outside the scope of this article.

3. Preparing the Empirical Analysis

3.1. *Empirical Strategy*

We begin by describing an approach to analysing our data which, although natural, we shall *not* take. We then explain how we will proceed. The approach which we shall not take is to postulate some stochastic version of straightforward bidding with private values, and then to estimate bidders' private values using discrete choice methods. This approach has been taken by Plott and Salmon (2004) who have considered the same data as we do. Their paper was written at the same time as ours and is independent of ours. They find that approximately 78% of all bids in the UK auction are consistent with the model and their estimates (leaving aside the random error which was inserted into the model for the estimation). Plott and Salmon also report percentages per bidder, and find that they vary significantly, from about 42% for Orange, over 77% for BT3G, to 100% for Vodafone. They also report other summary statistics.

Our approach is not to perform this overall estimation but to proceed in a sequence of steps. First, we ask how bidders chose which licence to bid for. Second we ask how bidders chose how much to bid. Finally, we ask how bidders chose when to withdraw from the auction. For simplicity we ignore the potential interdependence between answers to these questions. The reader will hopefully be convinced by our findings that this point is not important. Our approach takes a much more detailed look at the data than Plott and Salmon. We believe that our results below show that our approach allows us to understand much more precisely in which way different companies' behaviour deviated from the benchmark than Plott and Salmon's approach does.

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 of these licence to bid for. Finally, we ask how bidders decided whether to bid for a 'large' or a 'small' licence. Note the conditional nature of the first two questions. It turns out that the first and second part of the first step as well as the second and third step, do not reveal major deviations from our benchmark hypothesis. This will be demonstrated in the current Section. In the next Section we then focus on the third part of the first step, i.e. on the choice between a large and a small licence. This turns out to be the most interesting part of our empirical analysis.

[10] The intuition is that the claim is analogous to the well-known fact that 'one best reply to Markov strategies is a Markov strategy'.

Step 1A: 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. According to our benchmark hypothesis, 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. We call in Figure 1 the minimum admissible bid for licence A the 'price of A' and the minimum admissible bid for licence B the 'price of B'. We shall use this and analogous terminology throughout the paper.

Figure 1 shows that in most rounds the difference between the price of A and the price of 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 competition for licence B which is due to the restriction that incumbents could bid only for B but not for A.

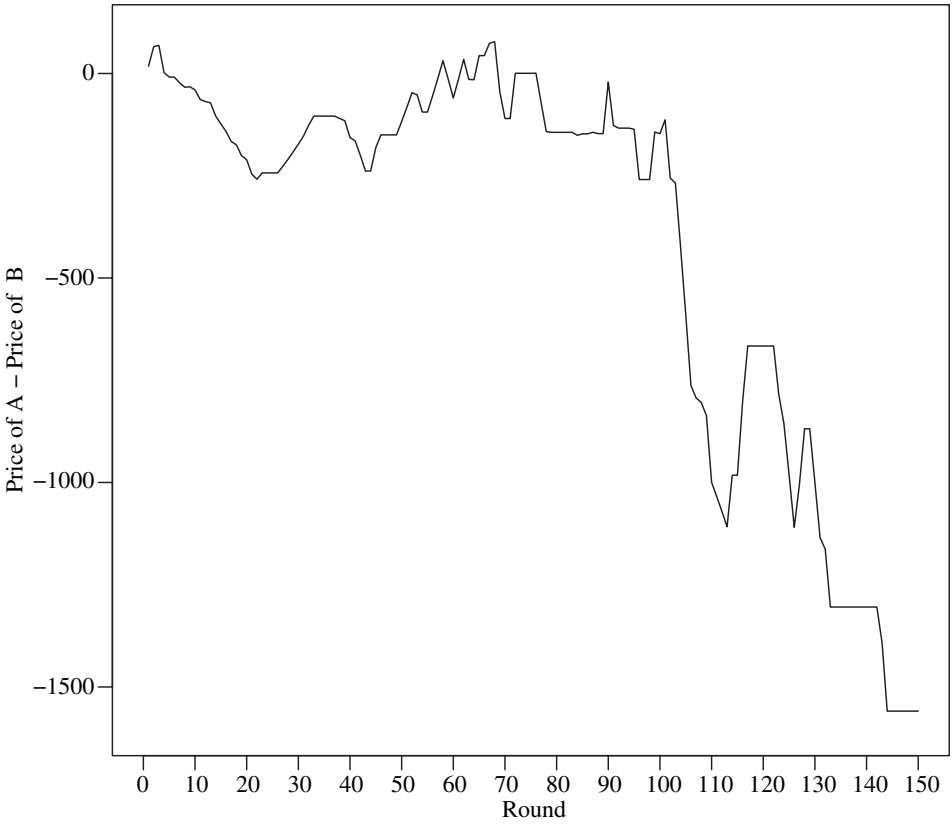

Fig. 1. *Price of A – Price of B* (in £ million)

Table 3

Valuation of A – Valuation of B (Upper and Lower Bounds)

Company	Largest Lower Bound	No. of Bids for A	Smallest 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

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: 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 under our benchmark hypothesis 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. To see this formally, let us denote the company's valuation of licence A by v_A and its valuation of licence B by v_B. Also, denote the price of A in some particular round by p_A, and denote the price of B by p_B. The benchmark hypothesis says that a company will bid for A if and only if:

$$v_A - p_A \geq v_B - p_B \Leftrightarrow v_A - v_B \geq p_A - p_B.$$

Each round in which a bid for A is placed thus provides us with a lower boundary for $v_A - v_B$. We can summarise the information thus obtained by focusing on the largest lower bound. Similarly, we can also construct a lowest upper bound for $v_A - v_B$, by considering the price differences in those periods in which the company bid for licence B. Table 3 shows for each of the three companies in question the largest lower as well as the lowest upper bound, and also the number of observations on which these bounds are based.

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 million and £65.7 million. For Spectrumco we deduce that any value difference which Spectrumco perceived must have been extremely small. TIW is problematic. Its 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. There is no valuation difference which can rationalise TIW's bidding behaviour. The violation of our basic hypothesis is, however, 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 which only bid for A but nor for B.

Step 1B: How did bidders choose whether to bid for licences 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

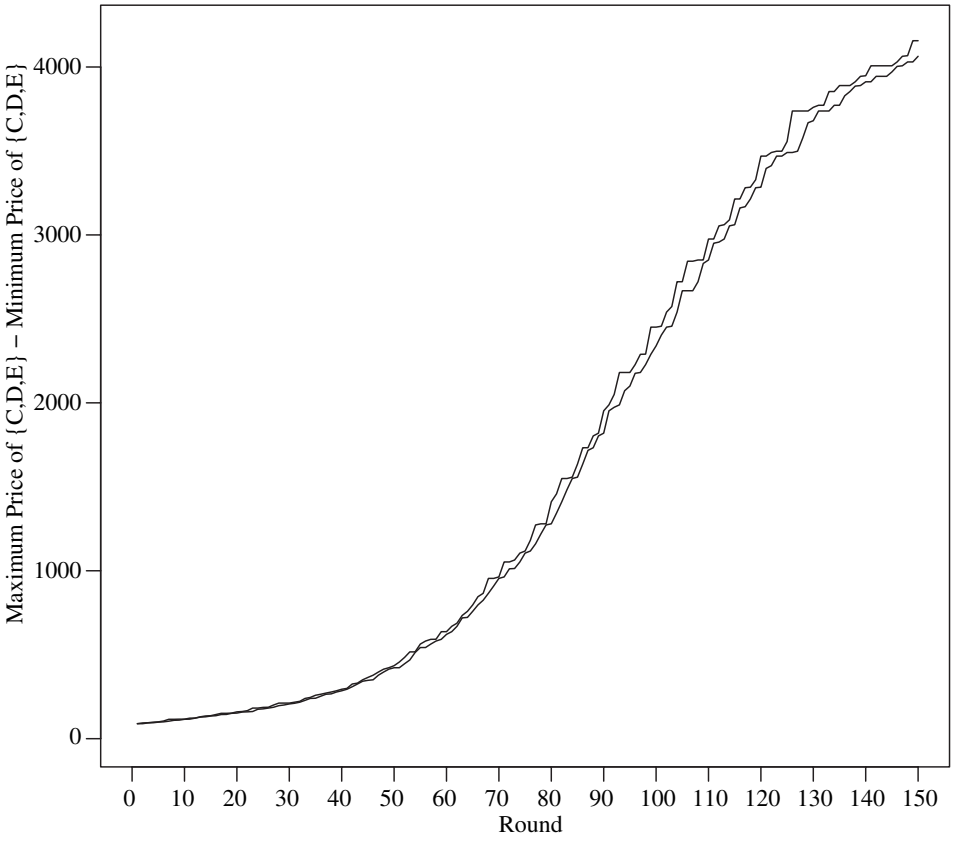

Fig. 2. *Maximum Price of* {*C, D, E*} – *Minimum Price of* {*C, D, E*} (in £million)

bidders might have had preferences for particular frequencies for technical reasons. Under our assumptions, if companies were indifferent between C, D and E, they should always bid for the licence which currently had the lowest price. We now investigate whether this was indeed the case, or how bids deviated from this rule.

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. There was therefore no possibility of large deviations from the predictions of our benchmark 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 benchmark assumptions and the hypothesis that licences C, D and E were identical. Two others, One2One and Worldcom, deviated so rarely from the benchmark 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.[11] Only two of the 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 priced at £ 3,281 million. 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 which 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 rationalise 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). Specifically, we assume that a bidder picks in each round the licence ℓ for which $v_\ell - p_\ell + \varepsilon_\ell$ is largest, where ε_ℓ is an extreme value distributed random variable which is i.i.d. across licences and periods. Our data allow us to identify value differences as well as the standard deviation of ε_ℓ. Estimates of these variables are reported in Table 4.

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, it might be that companies have tried to avoid ties. In the absence of jump bidding there will typically be a tie for the cheapest licence, and a company might be better off bidding for the second cheapest licence, than tieing with the other companies, and then having to bid one further increment.[12]

Table 4

Estimated Value Differences (in £million)

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

[11] 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. We shall therefore ignore round 76 when considering One2One's bidding behaviour.

[12] A similar rationale can be given for jump bidding; see below.

Table 5
Distribution of Jump Bid Sizes

	Size of the jump bid						
Rounds	0%	<1%	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

Note Rows are percentages and sum to 100.

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 so much more valuable than licences C and D that the difference in value in each round was at least as large as the difference between the price of E and the prices of C or D.

Step 2: 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, when placed, were the largest bids for that licence, but also bids for which this was not true.

One possible rationale for jump bidding might be that bidders tried to avoid ties. The idea is similar to the rationale which we gave in the previous step for bids which were not placed on the cheapest of the small licences. By making a small jump bid a bidder could try to avoid ties with the other bidders and thus reduce the probability that he would have to raise his bid by another increment next round. 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.

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 rows of Table 5 do not differ significantly (5% significance level) from each other.

An interesting detail is that Vodafone placed only two jump bids, in rounds 123 and 143, and that the latter bid clinched licence B for Vodafone.

Step 3: How did bidders choose when to drop out of the auction?

Table 2 indicates that the first five bidders to withdraw from the auction did so in extremely close succession, in rounds 94–100. The remaining three withdrawals were much more evenly spaced. In rounds 94-100 the minimum admissible bid that needed to be placed to stay in the auction had reached around £ 2,000 million, i.e. about one half of the lowest winning bid. One possible explanation why so many bidders' withdrawal points are so close to each other is that informational considerations played a role, and that the first withdrawal led others to revise their estimates of the value of the licences in a way which made it 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 the withdrawals in rounds 94–100 were dictated by budget constraints i.e. that these five firms withdrew when they ran out of funds to pay for their bids.[13] 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.

4. The Choice Between a Large and a Small Licence

The remaining issue is how bidders chose whether to bid for a large or a small licence. We divide bidders into four groups and discuss the behaviour of bidders in these four groups in turn. The first group consists of the incumbents. 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.

4.1. *Incumbents*

The largest incumbent, 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. Thus, their behaviour suggested that they attached only a very small extra value, if any at all, to having a large licence.

Orange and BT3G switched back and forth between a small and a large licence. Orange's behaviour was approximately consistent with the benchmark hypothesis, whereas BT3G's behaviour was not. We illustrate the difference between the behaviour of Orange and that of BT3G in Figures 3 and 4. Both Figures show a

[13] See also our comments on financial externalities in Section 5.

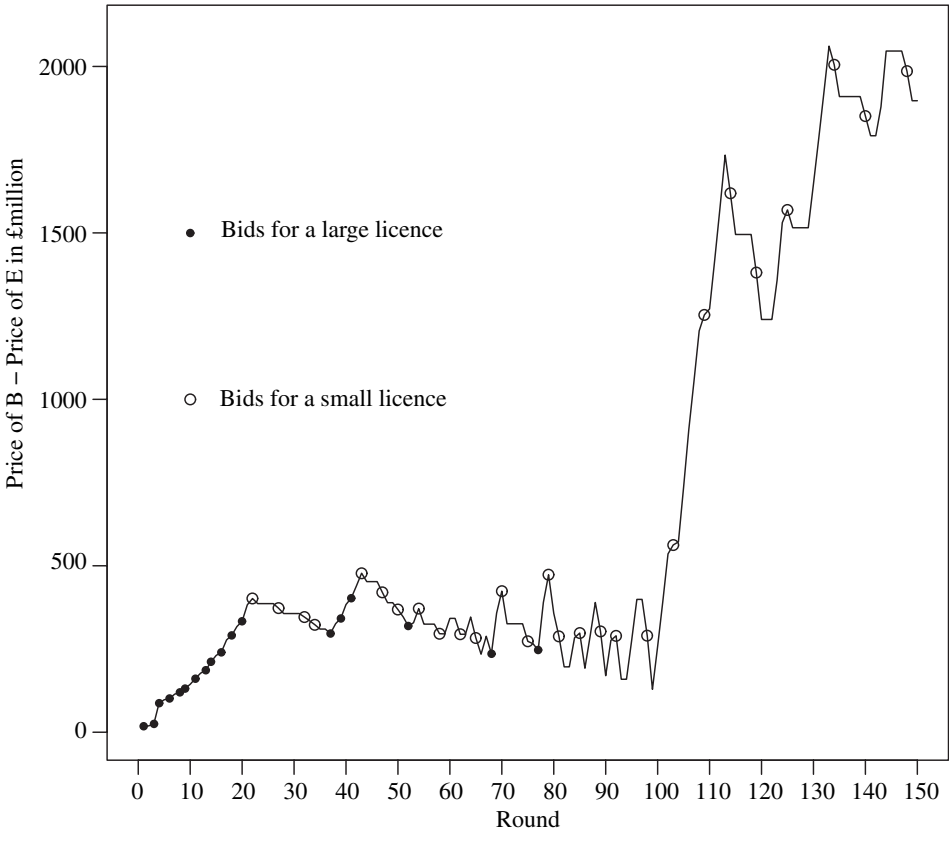

Fig. 3. *Orange's Bids for Large and Small Licences*

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 firms' 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 filled circle, and rounds in which a bid for a large licence was made are marked with an open circle. Bidding is consistent with our hypothesis of private values and straightforward bidding if one can draw a horizontal line through the figure so that all filled circles lie below the horizontal line and all open circles 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 large and a small licence.

In Figure 3 such a separating line can be drawn for Orange at around £300 million. In Figure 4, however, for BT3G no such separating line exists. Note that

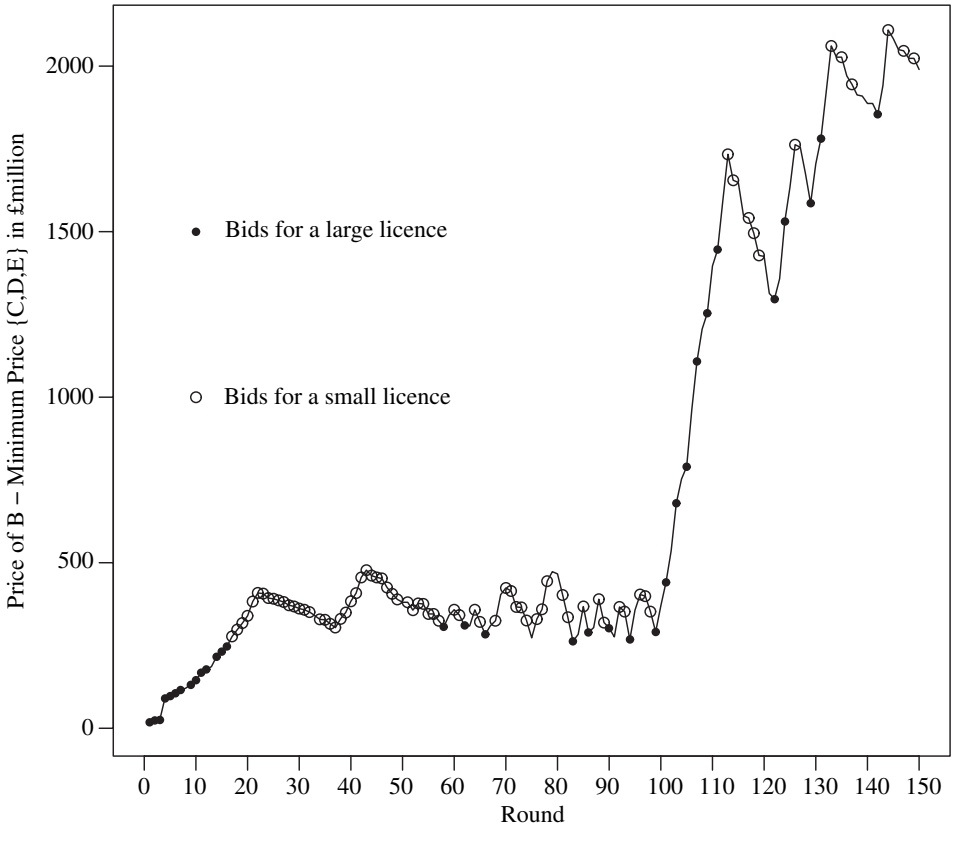

Fig. 4. *BT3G's Bids for Large and Small Licences*

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 was approximately the same as that of Orange, perhaps around £300 million. From round 101 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, and soon exceeded £1,000 million. 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.

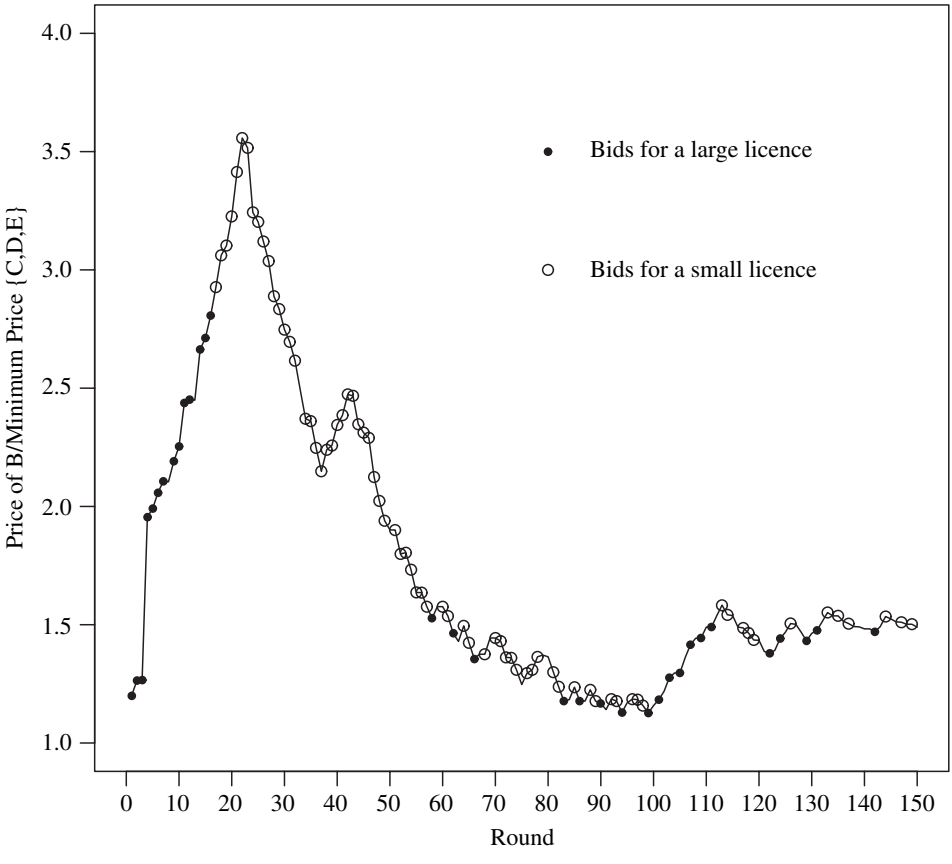

Fig. 5. *BT3G's Bids for Large and Small Licences* (the ratio rule)

It turns out that BT3G followed a different behaviour rule from rounds 101 onwards.[14] Instead of the price *difference* it was the price *ratio* that determined which licence BT3G would bid for next. Price ratios are shown in Figure 5. Figure 5 indicates that from round 101 onwards BT3G bid for licence B whenever the price ratio was below 1.5, and it bid for a small licence otherwise. Among the 23 bids which BT3G made from round 100 onwards only three bids deviated from this rule. These bids were made in rounds 117, 118 and 119 when B T3G bid for a small licence although the price ratio was lower than 1.5.[15]

Observe that 1.5 is exactly the ratio of the MHz of paired spectrum offered by licence B and the small licences. Thus, by following the 'ratio rule' BT3G chose its bids to minimise the money bid per MHz. Minimisation of average costs is, of course, different from profit maximisation. The question thus arises why BT3G adopted this rule. As far as we can see no other company adopted a similar rule. We shall speculate about possible rationales for BT3G's behaviour in the next Section.

[14] We are grateful to Michael Hodson for suggesting to us to consider price ratios.
[15] The price ratio in these rounds was: 1.4865 (round 117), 1.4652 (round 118), 1.4353 (round 119).

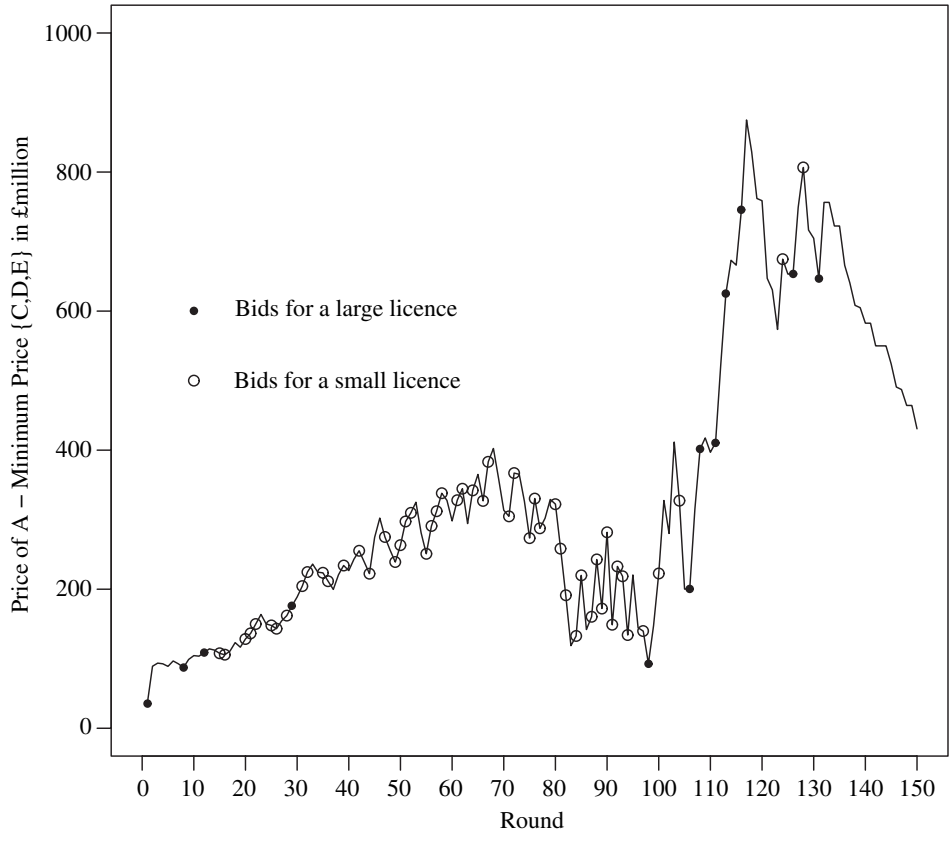

Fig. 6. *TIW's Bids for Large and Small Licences*

4.2. *TIW*

TIW's bidding, like BT3G's bidding, deviates substantially from our benchmark. Figure 6 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 6 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 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 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

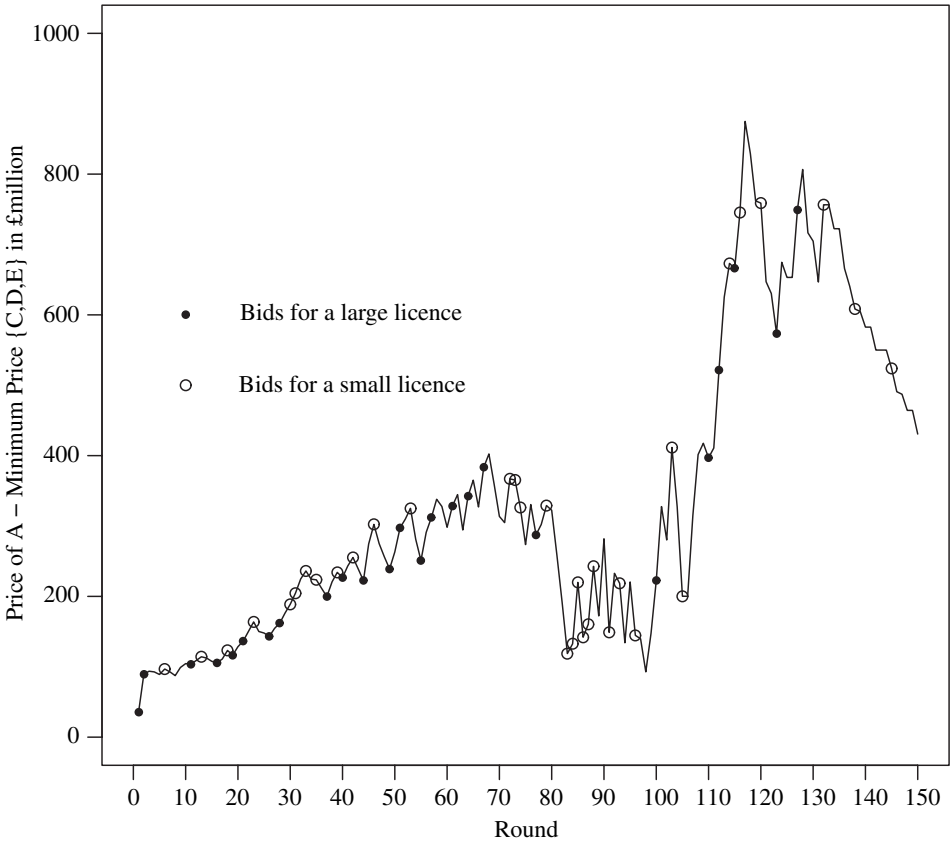

Fig. 7. *NTL Mobile's Bids for Large and Small Licences*

licence. As Figure 6 makes transparent, even if we focus on rounds 100–150, TIW's behaviour is not consistent.

4.3. *Outsiders Who Participated Beyond Round 100*

None of the three companies in this category, NTL Mobile, Telefonica, and Worldcom, bid in accordance with our hypothesis. We observe the biggest deviations for NTL Mobile. 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 7 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 7 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

they frequently switched between bidding for a large and a small licence, and they were 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. The largest price difference at which NTL Mobile was willing to bid for A was in round 127 (£749.2 million). The most remarkable fact about NTL Mobile's bids is that it ceased to bid for licence A after round 127 even though the price difference subsequently fell, and was only £381.1 million at the end of the auction.

4.4. *Outsiders Who Quit the Auction Between Rounds 94 and 100*

In this group, 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.[16] We focus on Spectrumco who bid more actively for a large licence, and whose behaviour we show in Figure 8. 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 8 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 8 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.

5. Explanations

We have seen that the most important discrepancy between our benchmark hypothesis and the actual bidding behaviour concerns bidders' choices whether to bid for a large or a small licence. In this Section we discuss possible explanations of these choices.

5.1. *Bidding in Early Rounds is Arbitrary*

The fact that many companies' behaviour seems to change significantly around round 100 of the auction might be attributed to the fact that before round 100 it

[16] As an aside we note that 3G UK's last two bids for a large licence (rounds 66 and 89) were placed on Fridays. These bids were not overbid in later rounds on those days, and 3G UK went into the weekends as the leading bidder for one of the large licences. 3G UK might have placed those bids to obtain publicity in the weekend press.

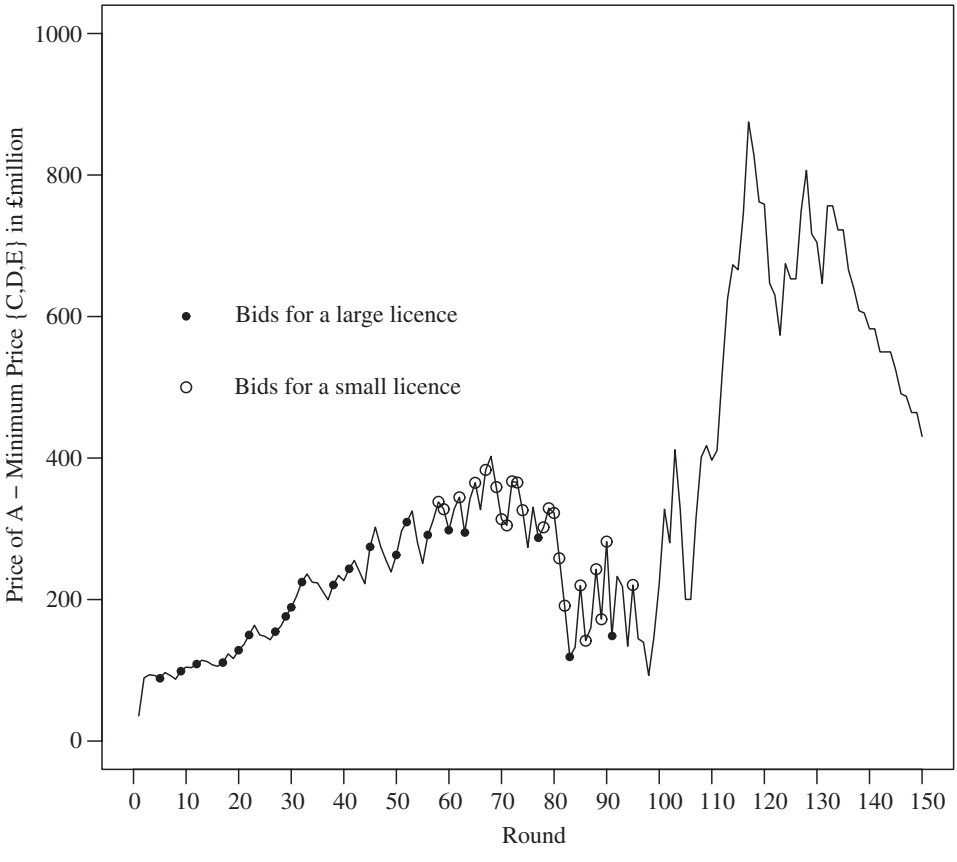

Fig. 8. *Spectrumco's Bids for Large and Small Licences*

was clear that the auction would not end soon. Therefore arbitrary bids could be placed without big risks. Around round 100 five bidders left the auction, and therefore bidding became more serious. We point out, however, that most bidders' behaviour in the first 100 rounds of the auction does not appear *arbitrary*. It often seems to follow clear principles but these principles differ from the strategies adopted later in the auction. For example, as explained above, BT3G's behaviour in the first 100 rounds of the auction seems very consistent. The problem is that the valuation difference revealed in these rounds seems not to have applied for later bidding. BT3G might have had purposes different from myopic surplus maximisation in the first 100 rounds, and we shall discuss this possibility in more detail below, but its behaviour does not appear *arbitrary*. We also note that not *all* bids in first 100 rounds could be regarded as riskless. For example, from round 78 onwards only BT3G and Vodafone bid for licence B. Thus, any bid for licence B involved the risk of being the winning bid. Finally, we note that many of the inconsistencies described in the previous Section concern rounds 100–150 only. We conclude that the evidence offered in this paper cannot be dismissed with the argument that early rounds did not matter.

5.2. *Rate of Return Maximisation*

The ratio rule adopted by BT3G in the second part of the auction might indicate that BT3G's profit maximisation calculation was different from that assumed by our benchmark hypothesis. Instead of seeking to maximise absolute profit levels, i.e. $v_\ell - p_\ell$, the value of licence ℓ minus the costs of licence ℓ, BT3G might have sought to maximise its rate of return, i.e. v_ℓ / p_ℓ. Straightforward bidding would then imply that BT3G would bid for licence B rather than, say, licence C if and only if

$$\frac{v_B}{p_B} \geq \frac{v_C}{p_C} \Leftrightarrow \frac{p_B}{p_C} \leq \frac{v_B}{v_C}.$$

Here, we take licence C to be representative of any of the small licences. If it happened to be the case that v_B/v_C was exactly equal to 1.5, then the ratio rule which we observe in the last 50 rounds of the auction results.

Maximisation of the rate of return rather than the absolute profit value might have been motivated by the fact that BT3G needed to attract investors. Investors will invest their funds in a variety of projects, and even if projects are indivisible investors will initially give priority to projects with the highest rate of return, and will take the size of the project into account only when they approach their budget constraint (which might be very different from BT3G's budget constraint). This explanation seems plausible, except that it appears to be a remarkable coincidence that v_B/v_C was exactly equal to 1.5, i.e. the ratio of the sizes of the licences in MHz. *Ex ante* there seems to be no reason why the value of a licence should be proportional to the size of that licence in MHz given that licences are not divisible. It is also somewhat surprising that there is no other bidder who adopted a similar strategy.

5.3. *Budget Constraints*

It seems plausible that the bidders in the UK auction faced budget constraints. The government had offered successful bidders two options for paying for their licences: instantaneous payment after the end of the auction, or deferred payment where 50% had to be paid instantaneously and the remaining 50% plus interest had to be paid over the next five years.[17] Companies seem to have regarded the option of deferred payment as too costly (National Audit Office, 2001, p. 31). Bidders probably arranged their funding before and during the auction. Apparent changes in bidding strategies during the auction may be due to changes in companies' financial situation.

If budget constraints were important, then companies might also have used the auction to influence their competitors' financial position adversely. One purpose might have been to reduce competitors' ability to finance the investment necessary to develop a third generation mobile phone network in the UK. Another purpose might have been to reduce competitors' ability to bid in the

[17] Special rules applied to Vodafone and Orange because of the connection created between these two companies by Vodafone's successful takeover of Mannesmann, which owned Orange.

European spectrum auctions which followed the UK's auction. Both considerations would give companies an incentive to raise the price which competitors' had to pay. Such behaviour might imply observed deviations from straightforward bidding.[18]

We now consider the extent to which these arguments explain the behaviour described in the previous Section. We begin with BT3G. Their increased willingness to bid for licence B from round 100 onwards might have been due to the fact that they could increase their credit lines at that stage. Up to round 98 the largest bid by BT3G had been £2,339.9 million. In round 99 they made their first bid above £2,500 million.

One might also speculate that the ratio rule which BT3G adopted after round 100 was motivated by budget considerations.[19] BT3G might have placed its bids for licence B primarily with the intention of raising the price which Vodafone had to pay, not with the intention of winning the licence. BT3G might have believed that Vodafone had a limited budget for spectrum auctions, and that exhausting Vodafone's budget in the UK auction would lead to advantages for BT3G in later auctions. The main problem with this hypothesis is that BT3G would have had to fear that Vodafone might not overbid one of its bids for B, and that it would then have to buy B at the price which it had bid. Perhaps BT3G held beliefs about Vodafone's strategy according to which this risk appeared small. Suppose, in particular, that BT3G believed for some reason that Vodafone valued any of the small licences at v and the large licence B at $1.5v$. BT3G might not have known the value of v. But, by never letting the price of B rise above 1.5 times the price of a small licence, BT3G might have thought that it could at least ensure that Vodafone would bid for B as long as Vodafone stayed in the auction. Moreover, BT3G might have felt confident that the risk that Vodafone would withdraw from the auction altogether was very small.

Although this is an interesting speculation, we are not convinced by it. Vodafone was financially much stronger than BT3G. It would have made much more sense for Vodafone to raise the price which BT3G had to pay than the other way round. Moreover, it is unclear how BT3G would have arrived at the belief that Vodafone valued a large licence at exactly 50% more than a small licence. The bids placed by Vodafone in the auction did not provide any evidence supporting this belief. On the other hand, BT3G may have had evidence external to the auction that Vodafone was pursuing this strategy. As an aside we note that the above discussion illustrates that Vodafone's strategy of evidently only bidding for B exposed it to predatory bidding by other bidders. It is therefore puzzling why Vodafone pursued this strategy.

[18] The possibility that bidders in spectrum auctions might seek to raise the prices paid by others was raised by Maasland and Onderstal (2002). Theirs is a theoretical paper which focuses on the case that only one unit is for sale.

[19] We are grateful to Paul Klemperer for first suggesting the following argument to us. See also Klemperer (2002*b*), where the argument is further developed. We express in the main text of the current paper, and also in Börgers and Dustmann (2002*b*), scepticism towards this explanation of BT3G's behaviour. However, Dan Maldoom's comment that is published with this paper supports Klemperer's argument. We have left the main text of the current paper unchanged so that readers can see our assessment as it was before we received Dan Maldoom's comments.

As far as other bidders are concerned the only case where budget constraints might have played a role is NTL Mobile. Specifically, the reason why NTL Mobile stopped bidding for licence A in the final rounds of the auction although the difference between the price of A and the price of the smaller licences dropped dramatically might have been that NTL Mobile had hit a budget constraint. NTL Mobile's last bid for A was in round 127 when it bid £4,277.7 million. This bid was overbid by TIW in round 131. NTL Mobile did not bid again for licence A. To overbid NTL Mobile would have had to bid £4,494.4 million. NTL Mobile instead bid for smaller licences, with its highest subsequent bid being £3,970.5 million. Thus it may well have been that NTL Mobile had a budget constraint of, say, £4,300 million.

5.4. *Information Effects*

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

It is plausible that some such process of information gathering has taken place during the auction. However, it is difficult to believe that these effects were the main source of phenomena of the size which we found in the previous Section. The uncertainty surrounding the third generation mobile telephone market was very large, and it seems hard to believe that at the time of the auction any of the bidders held important hard information that was not public knowledge.

Even if information effects were relatively small, though, it could be that bidders anticipated these informational effects and tried to manipulate the inferences which competitors could draw from their actions. In particular, it seems possible that BT3G and TIW tried to conceal in the first 100 rounds of the auction their true valuation of a large licence. The goal might have been to induce other bidders to drop out of the auction. If such concealment was indeed intended, it is interesting that the two companies followed different strategies. BT3G tried to indicate that its evaluation of the difference between a large and a small licence was the same as that of other bidders, in particular Orange. By contrasts, TIW almost never bid for a large licence in the first 100 rounds.

5.5. *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 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.[20]

In our companion paper, Börgers and Dustmann (2002*a*), we have scrutinised the bids of three selected companies, BT3G, TIW, and NTL Mobile, for evidence of allocative externalities. We have not found any clear indication that such externalities played a role in the UK auction. Our approach in the companion paper is based on the assumption that companies expect the current leaders on licences also to be the final winners of these licences.[21] We then ask whether conditional on certain salient features of the current positions in the auction, such as who currently leads on licence A, bidders' behaviour reflects consistent estimates of the difference in value between a large and a small licence. We find that this is not the case.

5.6. *Shareholders' Opinion*

Bidders in the auction are likely to have monitored the views of their shareholders carefully. These views might have expressed themselves in share prices.[22] Managers might, for example, have found that the share price responded very negatively to particular bids, and might have avoided similar bids in the future. This might explain some of the apparent changes of bidding strategy which we have found in the data. In our companion paper, Börgers and Dustmann (2002*a*), we have investigated in detail the short-run behaviour of the share prices of British Telecom, TIW and of the joint owners of NTL Mobile, i.e. NTL and France Telecom. We have found no clear evidence that the share prices of these companies influenced their behaviour.

Although we have not found specific influences of share price movements *during* the auction on the bidding in the auction, it is possible that concerns about how the stock market would react *after* the auction influenced bidding in the auction. In particular, this might offer another explanation for BT3G's behaviour.[23] BT3G might have assumed that the stock market would evaluate its performance in the auction by comparing the price per MHz paid by BT3G to the price per MHz paid by other companies. The ratio rule ensured that by this criterion BT3G performed no worse than Vodafone. There is no evidence to support or refute this theory.[24]

[20] Jehiel and Moldovanu (2000) and (2001) have suggested that such externalities were important in the European spectrum auction. However, in their empirical discussion 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.

[21] Our analysis also assumes straightforward bidding. 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 unknown there is also no strong reason to believe that bidders would employ equilibrium strategies.

[22] We would like to thank Philip Kalmus for suggesting we consider share prices.

[23] This argument was suggested in Klemperer (2002*b*). Klemperer (2002*c*) suggests that relative performance concerns played a role in Germany's third generation telecom auction.

[24] Our earlier discussion, in the context of the possible relevance of budget constraints, about possible risks of the ratio rule applies here as well.

5.7. *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's 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 these companies. We have no direct evidence to support this suggestion. But 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 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".' Despite 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.

6. Concluding Remarks

Spectrum auctions are often described as grand successes for auction theory. In the case of the UK 's UMTS spectrum auction, however, we have found significant discrepancies between actual bidding and the most prominent bidding theory that might be relevant to this auction, straightforward bidding with private values. We have also found that some bidding behaviour was is in accordance with this theory. We have discussed hypotheses that might account for the deviations which we found, but only some of these seemed promising. Formal theories that incorporate the more promising hypotheses still need to be developed further.

Finally, we emphasise again that this article does not imply that the allocation of licences resulting from the auction that we have studied was inefficient. As we mentioned already in the Introduction, what can be concluded from our analysis is only a conditional statement: If efficiency was achieved, then it was not for the reasons that are analysed in the main body of auction theory, but for some other reason. The question whether efficiency was actually achieved is beyond the scope of our analysis.

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References

Ausubel, L., Cramton, P., McAfee, P. and McMillan J. (1997). 'Synergies in wireless telephony: evidence from the broadband PCS auctions', *Journal of Economics and Management Strategy*, vol. 6(3), pp. 497–527.

Binmore, K. and Klemperer, P. (2002). 'The biggest auction ever: the sale of the British 3G telecom licences', Economic Journal, vol. 112, pp. C74–96.

Börgers, T. and Dustmann, C. (2002*a*). 'Rationalizing the UMTS spectrum bids: the case of the UK auction', *ifo Studien*, vol. 48(1), pp. 77–109; reprinted in (G. Illing and U. Klüh, eds.), *Spectrum Auctions and Competition in Telecommunications*. Cambridge: MIT Press, 2004.

Börgers, T.and Dustmann, C. (2002*b*). 'The British UMTS auction: a response to Klemperer and Schmidt', *ifo Studien*, vol. 48(1), pp. 121–2; reprinted in (G. Illing and U. Klüh, eds.), *Spectrum Auctions and Competition in Telecommunications*. Cambridge: MIT Press, 2004.

Börgers, T. and Dustmann, C. (2003). 'Awarding telecom licenses: the recent European experience', *Economic Policy*, vol. 36, pp. 215–68.

Cable, J., Henley, A. and Holland, K. (2002). 'Pot of gold or winner's curse? An event study of the auctions of 3G mobile telephone licences in the UK', *Fiscal Studies*, vol. 23(4), pp. 447–62.

Cramton, P. (2001). 'Lessons learned from the UK 3G spectrum auction, report for the National Audit Office', Reproduced in National Audit Office, *The Auction of Radio Spectrum for the Third Generation of Mobile Telephones*, pp. 47–55.

Cramton, P. (2002). 'Spectrum auctions', in (M. Cave, S. Majumdar and I. Vogelsang, eds.), *Handbook of Telecommunications Economics*, Chapter 14, pp. 605–39, Amsterdam: Elsevier Science B.V.

Cramton, P. and Schwartz, J. (2000). 'Collusive bidding: lessons from the FCC spectrum auctions'. *Journal of Regulatory Economics*, vol. 17(3), pp. 229–52.

Cramton, P.and Schwartz, J. (2002). 'Collusive bidding in the FCC spectrum auctions', *Contributions to Economic Analysis & Policy*, vol. 1:1, available at: www.bepress.com.

Demange, G., Gale, D. and Sotomayor, M. (1986). 'Multi-item auctions', *Journal of Political Economy*, vol. 94(4), pp. 863–72.

Jehiel, P. and Moldovanu, B.(2000). 'An economic perspective on auctions', *Economic Policy*, vol. 36, pp. 269–303.

Jehiel, P. and Moldovanu, B. (2001). 'The European UMTS/ IMT-2000 licence auctions', mimeo., ELSE and Universität Mannheim.

Klemperer, P. (2002*a*). 'How (not) to run auctions: the European 3G telecom auctions', *European Economic Review*, vol. 46(4-5), pp. 829–45; reprinted in (G. Illing and U. Klüh, eds.), *Spectrum Auctions and Competition in Telecommunications*, Chapter 7, Cambridge: MIT Press 2004 and in (P. Klemperer), *Auctions: Theory and Practice*, Chapter 5, Princeton and Oxford: Princeton University Press, 2004.

Klemperer, P. (2002*b*). 'Some observations on the British 3G telecom auction: comments on Börgers and Dustmann', *ifo Studien*, vol. 48(1), pp. 115–20; reprinted in (G. Illingand U. Klüh, eds.), *Spectrum Auctions and Competition in Telecommunications*, Chapter 10, Cambridge: MIT Press, 2004 and in (P. Klemperer), *Auctions: Theory and Practice*, Chapter 7, Princeton and Oxford: Princeton University Press, 2004.

Klemperer, P. (2002*c*). 'Some observations on the German 3G telecom auction: Comments on Grimm, Riedel and Wolfstetter', *ifo Studien*, vol. 48(1), pp. 115–20; reprinted in (G. Illing and U. Klüh, eds.), *Spectrum Auctions and Competition in Telecommunications*, Chapter 15, Cambridge: MIT Press, 2004, and in (P. Klemperer), *Auctions: Theory and Practice*, Chapter 7, Princeton and Oxford: Princeton University Press, 2004.

Leonard, H. (1983). 'Elicitation of honest preferences for the assignment of individuals to positions', *Journal of Political Economy*, vol. 91(3), pp. 461–79.

Maasland, E. and Onderstal, S. (2002). 'Auctions with financial externalities', mimeo., CentER, Tilburg.

McAfee, P. and McMillan, J. (1987). 'Auctions and bidding', *Journal of Economic Literature*, vol. 25(2), pp. 699–738.

McFadden, D. (1974). 'Conditional logit analysis of qualitative choice behavior', in (P. Zarembka, ed.), *Frontiers in Econometrics*, pp. 105–42, New York: Academic Press.

McMillan, J. (1994). 'Selling spectrum rights', *Journal of Economic Perspectives*, vol. 8(3), pp. 145–62.

Milgrom, P. (2000). 'Putting auction theory to work: the simultaneous ascending auction', *Journal of Political Economy*, vol. 108(2), pp. 245–72.

National Audit Office (2001). *The Auction of Radio Spectrum for the Third Generation of Mobile Telephones*, London: The Stationery Office.

Plott, C. and Salmon, T. (2004). 'The simultaneous, ascending auction: dynamics of price adjustment in experiments and in the UK3G spectrum auction', *Journal of Economic Behavior and Organization*, vol. 53(3), pp. 353–83.

N. M. Rothschild & Sons (1999). 'United Kingdom spectrum auction: the next generation of mobile communications, preliminary information memorandum', London.

Radiocommunications Agency and N. M. Rothschild & Sons (1999). 'United Kingdom spectrum auction: the next generation of mobile communications, information memorandum', London.

The Independent on Sunday (2001). 'Bland: BT wrong to bid for 3G' (by Clayton Hirst), 29 April, p. 1.

UMTS Auction Consultative Group (1998). 'Minutes of the meeting on 13 November 1998' (including the document UMTS Auction Design (2), UACG (98) 16), available at: http://www.ofcom.org.uk/static/archive/spectrum auctions/3gindex.htm.

UMTS Auction Consultative Group (1999). 'Minutes of the meeting on 14 May 1999', (including the document UMTS Auction Design (4), UACG (99) 17), available at: http://www.ofcom.org.uk/static/archive/spectrum auctions/3gindex.htm.
UMTS Forum (2001). 'What is UMTS?' and 'About us', available at: http://www.umts-forum.org/.