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THE GERMAN 4G SPECTRUM AUCTION: DESIGN AND BEHAVIOUR*

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The 2010 German 4G spectrum auction was an unusually large simultaneous ascending multi-band auction. The bidding was competitive and the final assignment was efficient. However, our analysis suggests that independent and rational bidders had an opportunity to coordinate implicitly on a low-revenue outcome. Coordination was difficult, though, because of a multiplicity of focal points. One important focal point involved post-auction negotiations, posing risks to bidders and the auctioneer. We analyse different bidding scenarios and how post-auction negotiations can affect values, bidding and efficiency. We also discuss how the simultaneous ascending auction format can be augmented to mitigate the risks.

Spectrum is an essential input in providing wireless communications. Since July 1994, spectrum auctions have been the primary means of assigning and pricing scarce spectrum. Most of these auctions are simultaneous ascending auctions in which all lots are auctioned simultaneously, the bidders raise their bids on individual lots in a series of rounds and the auction continues until no bidder is willing to bid higher on any lot.

The German 4G auction is an important example. The auction was unusual in the large quantity of spectrum that it awarded. It was for 41 nationwide spectrum blocks in four different spectrum bands, totalling 360 MHz of spectrum (290 MHz of paired spectrum and 70 MHz of unpaired spectrum). By comparison, the two most recent major auctions in the US were the 2006 AWS auction for 90 MHz of spectrum ($13.7 billion revenue) and the 2008 700 MHz auction for 62 MHz of spectrum ($19.6 billion revenue). Nearly all earlier spectrum auctions awarded spectrum in a single band.

The German auction ended successfully after 224 rounds of competitive bidding. There is no reason to suppose that the auction assignment is inefficient and the auction revenue was close to the range that was *ex ante* expected by some observers. However, there is a theoretical concern that the auction might have played out differently and that bidding might have led to an 'implicit coordination' arrangement on a low-revenue equilibrium. In its simplest form, the idea behind implicit coordination is that independent and rational bidders try to anticipate the outcome of competitive bidding and implicitly coordinate on this outcome early in the auction. The language of implicit coordination is bids in the auction.[1] If bidders' expectations

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[1] Throughout we use the term 'implicit coordination' and related terms in the economic sense of implicit communication through bidding, rather than in any legal sense.

turn out to be mutually consistent, the auction can end early, when prices are still low. That is, implicit coordination may avoid a price war that yields the same (efficient) assignment as competitive bidding but at lower prices. Under certain assumptions about how bids are interpreted, we show that low-revenue outcomes were a theoretical possibility in the German 4G auction. We also show that implicit coordination was practically complicated by the fact that there was a multiplicity of focal points to coordinate implicitly on.

With a multiplicity of low-revenue equilibria, successful implicit coordination on an equilibrium requires bidders to focus on a common focal point. As we explain below in more detail, there have been two major predictions about potential low-revenue auction outcomes in the German 4G auction, which might serve as focal points. Some observers expected that the allegedly weakest bidder, E-Plus, either would concede with respect to the important six 800 MHz blocks, or might attempt to reach a network sharing agreement. In fact, early bids could be interpreted as anticipating these predicted outcomes. In particular, E-Plus showed persistent interest in only one block in that spectrum band, although, because of complementarities, one single block in the 800 MHz band has little value to any bidder. While there may be multiple, complementary reasons behind E-Plus's strategy, one might hypothesise that one reason for demanding only one block was to improve E-Plus's negotiation power in post-auction negotiations on network sharing or on potential mergers. Our analysis suggests that this strategy can be interpreted as an attempt to coordinate implicitly on a low-price auction equilibrium, with E-Plus winning one 800 MHz block. However, the three competitors each submitted jump bids on two blocks in the 800 MHz band early in the auction, which suggested that they were not willing to make room in the 800 MHz band. E-Plus finally gave in. When the auction ended, the industry as a whole was more than €4 billion poorer and all bidders worse off compared to what probably might have been possible early in the auction.[2]

We explain how post-auction negotiations may affect values and bidding, and how this might have led to different paths of auction play, which in turn might pose risks both to the auctioneer and the bidders. Our study also suggests that by only slightly augmenting the design of the simultaneous ascending auction, such risks can be considerably mitigated.

1. The Economic Parameters of the German 4G Auction

1.1. *Supply*

Figure 1 shows that spectrum was offered in four frequency bands, starting at 800 MHz ('digital dividend'), 1.8 GHz, 2.0 GHz and 2.6 GHz respectively.[3] Each band has several blocks, marked with a capital letter, on which bidders can place bids. For example, there are six blocks (A–F) in the 800 MHz band. Most of the blocks are paired, comprising 2 × 5 MHz; blocks F and E in 2.0 GHz and blocks O–X in 2.6 GHz are the (unpaired) exceptions.

[2] Interestingly, despite E-Plus's failure to secure a block in the 800 MHz band, E-Plus's market share grew following the auction as shown in Table 1 below.

[3] More detailed information about the technical environment as well as the detailed auction rules can be accessed in German at Bundesnetzagentur (2010).

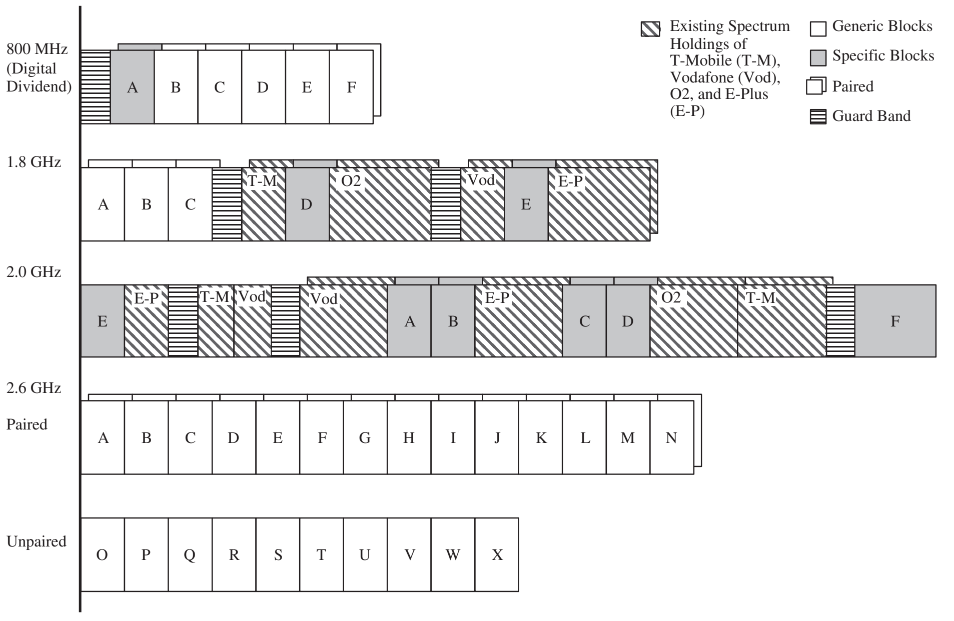

Fig. 1. *Spectrum Supply and Previous Holdings*

Bidding on generic blocks facilitates arbitrage among substitutes and thus improves competition (Cramton, 2013). In the German 4G auction, the blocks supplied in each band are divided into specific (grey in Figure 1) and generic (white) blocks. Block A in 800 MHz, for instance, is specific because it faces additional interference issues from TV broadcast and so was supposed to be worth less than the other blocks in that band, which are perfect substitutes. The high bidder on a specific block wins that specific frequency block. The specific frequencies of generic blocks are negotiated among winning bidders after the auction. If they fail to agree, the specific assignment is determined by the regulator based on efficiency (promoting adjacency of won and already held spectrum), or by randomising.

Figure 1 also shows existing spectrum holdings of the four existing mobile operators in the respective bands (diagonally striped blocks with small characters in the upper left corner indicating the respective operator). The next subsection argues that the locations of these holdings are of critical importance for the bidders' values and strategies.

1.2. *Demand*

One important feature of the German 4G auction is that only the four existing mobile operators participated: T-Mobile (since unification with Deutsche Telekom's business unit T-COM called Telekom Deutschland), Vodafone, O2 (a unit of Telefónica of Spain) and E-Plus (a unit of the Dutch operator KPN). Table 1 provides an overview of market shares and subscribers of the bidders at the time of the auction and four years later.

Table 1

Mobile Operators in Germany

	Market share (%)		Subscribers (millions)	
Operator	2010	2014	2010	2014
T-Mobile	34	32	39	37
Vodafone	30	29	35	34
O2	19	17	22	20
E-Plus	17	22	19	25
Total	100	100	115	116

Regarding values, analysts agreed that by far, the most attractive spectrum is the 800 MHz band, the digital dividend. This low-band spectrum allows better coverage both within buildings and in difficult terrain, and requires many fewer cell sites to provide coverage. Also, the digital dividend is characterised by strong complementarities: two blocks are worth much more than a single block, while a third block and further blocks have diminishing marginal values. However, because there are four bidders and only six digital dividend blocks are for sale, at least one of the four bidders must fail to win a package of two blocks.

A second driver for values comes from the fact that mobile broadband with 4G equipment is expected to be delivered using the long term evolution (LTE) technology. To achieve maximum data speeds, an operator needs 2 $\times$ 20 MHz of contiguous bandwidth; speed decreases with less contiguous bandwidth. Thus, although the preferences may differ across bidders depending on the specific portfolio and business plan, less than 2 $\times$ 20 MHz in one of the bands above 800 MHz typically reduces the usage flexibility and thus the per block value.

There are also complementarities in that the location of already held spectrum matters for the value of new spectrum: holding spectrum adjacent to a block makes the block more attractive. Figure 1 shows what is already held by the four bidders in the relevant bands. To see how the location of holdings matter, look at the E-block at 1.8 GHz, for instance. This block is likely to be worth much more to E-Plus than to O2. From O2's perspective, the 2 $\times$ 5 MHz E-block is isolated and thus is of small value; however, the E-block would nicely complement E-Plus's portfolio by lifting the bandwidth beyond the threshold of 2 $\times$ 20 MHz. Similarly, the blocks A, B and C at 1.8 GHz seem more attractive to T-Mobile than to any other carrier, while the blocks A and B at 2.0 GHz are likely worth more to both Vodafone and E-Plus than to T-Mobile and O2.

Finally, unpaired blocks are of less interest to bidders, and thus will play only a minor role in our analyses.

1.3. *Auction Rules*

The regulator chose to implement a simultaneous ascending auction in which all lots are auctioned simultaneously, the bidders raise their bids on individual lots in a series of rounds, and the auction continues until no bidder is willing to bid higher on any lot (Cramton, 2006 for a discussion of the format). This standard format was augmented by two rules.

First, the German regulator limited the buying rights of the two bigger operators, T-Mobile and Vodafone, which have a combined 64% market share, to a maximum of two blocks of the digital dividend each.[4] The bidding rights of O2 and E-Plus for the digital dividend were limited to three blocks each.

Second, each bidder could as part of its confidential auction application specify 'essential needs', that is a minimum number of blocks in the 800 MHz band and/or the other bands. Bidders must be active in all rounds on at least the number of 'essentially needed' blocks. If a bidder fails to win its essential needs, the bidder automatically loses all blocks.[5] The option can be attractive for new entrants, giving them a market exit strategy if they fail to win a profitable spectrum portfolio. However, as it turned out, only the existing mobile operators participated in the actual auction, which already hold spectrum across various bands. For these bidders, the 'essential needs' option seems less relevant. Moreover, the option cannot (and is probably not meant to) effectively protect these bidders against exposure or related problems because the essential needs cannot be adjusted to unexpected price developments. (Other design choices within the simultaneous ascending auction can sometimes protect against exposures; see Section 6 below.)

One peculiarity of the German 4G auction was that the feedback to bidders after each round included all bids and the respective bidders' identities. In line with an extensive literature on designing simultaneous ascending auctions, we show that this design feature tends to increase price risks, for example, by facilitating implicit coordination (see references below). Moreover, as shown in Figure 1 and discussed above, many blocks are generic. However, unlike in other simultaneous ascending auctions that use generic lots, bidders in the German 4G auction bid on individual lots, rather than on a quantity of the generic lots. This may further improve the scope for implicit communication through bidding, increasing strategic risks. We discuss potential implications for the German 4G auction in the following Sections.

Most of the other rules were standard.[6] The activity rule, for instance, stipulated that bidders need to be active on a certain number of blocks (or rather 'lots' that weighted blocks according to the respective bandwidth) in any of the four spectrum bands, in order not to lose bidding rights. The activity requirement ranged from 50% to 100% of the respective eligibility depending on the auction phase. Similarly, price increments, bid submission formats ('click-box bidding'), the ending rule, waivers and withdrawals were managed in ways similar to other auctions (Cramton, 2006).

[4] The smaller competitors, O2 and E-Plus, criticised the restrictions as too modest and unsuccessfully sued the regulator in order to achieve stricter restrictions for the two competitors.

[5] If because essential needs are not matched, or bids are withdrawn and the respective blocks do not get further bids, or for any other reasons some blocks remain unsold, the regulator reserved the right to decide if another auction is to be run. If the regulator does so, the same rules apply, but only bidders who win a block in the first auction can bid in the second auction.

[6] One minor peculiarity was that if several bids come in with the same price, the high bidder is selected by the earliest time stamp. Recent spectrum auctions implement a random selection rule in order to avoid too hasty bidding. Another peculiarity was that bidding took place in premises of German regulator BNetzA in Mainz where representatives of the bidders had to be physically present during the auction. They were connected by fax and telephone with their headquarters. Recent spectrum auctions outside Germany are organised on Internet-based platforms that allow participants to be geographically dispersed and to bid directly from their headquarter locations.

2. Implicit Coordination: Theory, Focal Points and Potential Gains

2.1. *Theory*

One simple baseline hypothesis about behaviour in simultaneous ascending auctions is that all bidders bid 'straightforwardly'. That is, they bid the minimum increment on all blocks as long as the respective current price is below the corresponding value (here, we abstract away from complementarities). However, economic theory and empirical evidence show that fully independent and rational bidders can be expected to 'reduce demand' in auctions for many items. That is, they bid less for items, or for fewer items than they want at the current price, in order to pay less for the items that they win. In particular, mutual demand reduction, or 'implicit coordination', can be an equilibrium in multiple-item auctions such as Germany's 4G auction. For theory, field and laboratory evidence on demand reduction and implicit coordination see, e.g., Wilson (1979), Klemperer and Meyer (1989), Cramton (1995, 2006, 2013), Engelbrecht-Wiggans and Kahn (1998), Wolfram (1998), List and Lucking-Reiley (2000), Jehiel and Moldovanu (2001), Kagel and Levin (2001), Cramton and Schwartz (2002), Klemperer (2002, 2004), Grimm *et al.* (2003), Wolak (2003), Milgrom (2004), Müsgens and Ockenfels (2011), Bolle *et al.* (2013), Ausubel *et al.* (2014) and the references cited therein.

The basic idea behind implicit coordination is to describe the auction as a 'coordination game', in which there are many equilibria, some possibly yielding low and others yielding high prices. From this perspective, the major challenge to bidders is to coordinate on an equilibrium. One potential way of doing this is for bidders to label those blocks that they would concede to others ('demand reduction') if this ends the auction. The references above provide many examples. In particular, jump bids, which are nearly cheap talk, could indicate demand the bidder is not willing to reduce, whereas minimum increment bids could indicate blocks the bidder may be willing to concede if this ends the auction. If the individual demand reductions are compatible with each other in the sense that all conflicts can be resolved, the auction may end. However, if there is excess demand even after considering possible demand reductions, implicit coordination fails and a higher revenue equilibrium may result.[7]

To make implicit coordination an equilibrium, bidders need to be confident that the auction will end with the respective concessions. The reason is that demand reduction implies a loss of eligibility to bid in the future, and so a weakened position that others

[7] Jump bids are common in spectrum (Börgers and Dustmann, 2005) and other auctions (He and Popkowski Leszczyc, 2013). Most models use signalling to explain jump bidding, and are mostly in line with our idea behind implicit coordination that we sketch above. One example is Grimm *et al.*'s (2003) analysis of the German GSM spectrum auction. Avery (1998) develops a more general model, with affiliated values, to show that jump bidding can serve to select the winner early in an auction. The reason is that aggressive jump bids can credibly signal a high type and thus induce weaker bidders to stop bidding at a price strictly below expected value (Hörner and Sahuguet, 2007). More recently, Ettinger and Michelucci (2015) have shown that jump bidding does not necessarily reveal information that helps facilitating coordination on low-revenue outcomes, but might also be rather used in an attempt to hide information about the drop-out price of some competitors and in this way may rise expected revenue. Finally, observe that, unlike in timber or electricity auctions, the context of spectrum auctions, including demand and supply characteristics, often strongly differs across auctions, which makes it difficult, if not impossible, to communicate and implicitly coordinate across such auctions. Yet, jump bids can be an effective mean of communicating and implicitly coordinating within a given auction context.

might exploit if implicit coordination fails. One way to achieve this confidence is to use a 'passive waiver'. In many auctions, including Germany's 4G auction, the passive waiver is automatically taken if a bidder does not bid at all in a given round and would otherwise lose eligibility. Unlike an 'active waiver', which has to be explicitly chosen before the end of the round, a passive waiver cannot prevent the auction from ending. This implies that, if in the end game all bidders utilise the passive waiver, bidders can test others' commitment to reduce demand without risking loss of eligibility. If implicit coordination fails, all bidders can bid as if there were no demand reductions.

While bidders may want to understate their willingness to reduce demand, this may be disciplined by the combination of three things. First, this increases the risk of a price war, which is an equilibrium, too and thus a credible threat. Moreover, practically, a price war may be difficult to stop once started. A bidding war will affect blocks with excess demand but it may also affect other blocks. The reason is that concessions in an implicit coordination might be made conditional on the auction ending and that a bidding war might involve costly punishment as well as costly management of eligibility. Second, if bidders have a good idea of other bidders' values, overstatements may not be credible. And third, bidders may care about fairness, which excludes extreme implicit coordination equilibria (see subsection 4.3).

Another framework for understanding behaviour is the behavioural focal point literature. A good example is Selten *et al.* (1997), which studies an asymmetric repeated Cournot game in the experimental laboratory. Subjects determined cooperative goals or 'ideal points' and then attempted to achieve cooperation with reciprocal movements toward or away from the ideal points. Translated to our context, bidders have certain ideas about 'ideal points' (such as the efficient, competitive outcome). They implicitly communicate through bidding what they might contribute (demand reduction) to reach these points and otherwise follow a measure-for-measure strategy. Both the ideal points and the strategy may be based on fairness or outside-option considerations.

2.2. *Focal Points*

Implicit coordination on a low-price equilibrium requires similar expectations among the independent bidders about which equilibrium to choose. Schelling's (1960) seminal work and considerable evidence (see, e.g., Isoni *et al.* (2014) and the references cited therein), suggest that naturally occurring, often highly context-specific focal points can help players to implicitly coordinate. Finding a focal point is particularly a challenge in complex auction environments, such as the German 4G auction (more spectrum, more bands, large asymmetries in bidders, values and holdings compared to other auctions). However, even in complex environments, focal points for implicit coordination may sometimes suggest themselves.[8]

[8] Understanding the scope for coordination in complex environments is an important issue also in other contexts. Weitzman (2014), Cramton *et al.* (2015) and MacKay *et al.* (2015), for instance, argue that a lack of a salient focal point for a vector of all countries' binding emissions quotas hampers coordination in international climate negotiations but that naturally occurring focal points regarding carbon price negotiations exist.

Natural focal points for implicit coordination in auction contexts are often those assignments that are commonly expected *ex ante*. One such focal point is the expected auction outcome with straightforward and competitive bidding (see Herweg and Schmidt (2014) and the references therein, for similar arguments). This predicted outcome will often be efficient, as well as fair in the sense that no bidder would fall behind its outside option assignment, which is reached in case implicit coordination fails.

Before the German 4G auction started, it was partly expected that the smallest and allegedly economically weakest competitor, E-Plus, would eventually fail to win two digital dividend blocks in competitive bidding. In fact, E-Plus fed such speculations. On 7 April 2010, a few days before the auction started, KPN released a 'KPN position paper' declaring that 'E-Plus will take a disciplined value-driven approach in the auction so that spectrum is only acquired at the right price. E-Plus expects to obtain a valuable combination of spectrum due to the large available amount of spectrum. Even without 800 MHz spectrum, E-Plus will execute planned coverage and capacity upgrades'. That is, an outcome with three bidders winning the digital dividend and E-Plus not winning, seemed to be part of a natural focal point for implicit coordination.

Other observers speculated that E-Plus might come to a network sharing agreement with the small but financially strong O2 after the auction. For instance, a *New York Times* article on 5 April 2010 speculated regarding the digital dividend that 'there is also the chance that O2 and KPN could cooperate' (see also the corresponding statements by the DZ bank below). Clearly, this outcome is more complicated because it would involve post-auction negotiations. We show later, however, that there is a corresponding auction outcome, in which both E-Plus and O2 win one digital dividend block respectively. This outcome, too, might serve as focal for an implicit coordination arrangement.

2.3. *Potential Gains*

The DZ bank estimated before the auction that if E-Plus or O2 were to concede at 800 MHz or if they manage to cooperate on network sharing – scenarios that the DZ bank calls 'peace' – the price of two blocks of the digital dividend would be only €5 million, while if none of the four bidders is willing to concede, the price would be €2 billion. That is, according to this estimate, the potential gains for T-Mobile, Vodafone and E-Plus or O2 from implicit coordination are almost €6 billion. The estimates of some other banks implied smaller profits from implicit coordination but of comparable magnitude. The actual costs of the bidders' failure to coordinate implicitly in the digital dividend band early in the auction were more than €4 billion. So, all four bidders had good reasons to assume that there are considerable gains from implicit coordination and that this is public knowledge among bidders.

3. Showing What You Want: The Three Allegedly Strong Bidders

Before we look at the bid data, we note that while all bidders were informed about all bids in each round, along with respective bidders' identities, our analysis makes use of the publicly released data which only provide information about the high bids in each round. A thorough analysis of competition in auctions typically requires an analysis of the full data set.[9] Fortunately, the high bid data in the German 4G auction are sufficient to speak to the key hypotheses regarding bidding strategies.

We have seen that rational independent bidders in the German 4G auction have an incentive to implicitly coordinate on a low-revenue outcome. Following the literature mentioned above, a natural way of communicating the degree of one's willingness to reduce demand is by submitting bids that are differentiated by the number of jumps over the minimum bid. By auction rule, the smallest jump in the German 4G auction is €10k, the next one €20k etc. A bid on a block with more jumps than other bids might be interpreted that the corresponding block has higher priority for that bidder. A bid with fewer jumps might reveal that the bidder is less interested and might even be willing to reduce demand of the corresponding block (although other interpretations are possible; see below).

Remarkably, all four bidders differentiated bids by different numbers of jumps in the very first auction round. This is true even though we cannot see losing bids (which were not made public), so this must also be true for the full bid patterns. From the publicly available data, T-Mobile, Vodafone and E-Plus chose jump levels that minimised the costs of the corresponding jump bid patterns (no jump, €10k or €20k jumps), while O2 decided to make their jumps more dramatic (€2 and €5 million). Nevertheless, none of the bids was likely close to values – and in this sense, all bids were nearly cheap talk. Following our analyses above, we now assume that high jump bids indicate 'high priority' bids (not to be conceded), while smaller or no jump bids indicate less interest and ultimately a readiness to reduce demand in an implicit coordination arrangement.

The public data suggest that T-Mobile, Vodafone and O2 used their respective largest jumps to bid on two blocks in the 800 MHz band. (E-Plus did not submit a high bid at 800 MHz in the first round.) So, under our assumption about how to interpret jumps, these three bidders are not willing to concede the digital dividend. At the same time, if we use our interpretation of jump bid patterns, these bidders might be willing to make some room outside the digital dividend if they get what they want in the 800 MHz band: all bidders submitted bids equal to the start price at other bands and blocks. For instance, the public data reveal that minimal (starting) bids were submitted by O2 at 2.0 GHz, by Vodafone at 2.6 GHz (paired) and by T-Mobile at 2.6 GHz (unpaired). However, because the public data do not give a full account of jump bid patterns, we – unlike the actual bidders – cannot be sure about the degree of excess demand with respect to high-priority bids outside 800 MHz.

We caution that different interpretations for jump bid patterns are possible. For instance, we cannot exclude the possibility that, by using jump bids, some bidders wanted to make sure that the competitors, the public and stakeholders can clearly observe their commitment to win certain blocks in certain bands at the beginning of

[9] We cannot think of any good reason for this selective information policy. In general, if there is full transparency among the bidders, the bids should also be publicly revealed so that the auction can be studied by all. The bidding data that were made public can be accessed at Bundesnetzagentur (2010) and on our web site.

the auction, with no intention of implicitly coordinating demand reductions. Also, a willingness to make room outside 800 MHz conditional on winning 800 MHz might just reflect decreasing marginal value of spectrum, and so may not be related to a demand reduction strategy. However, because bidders are likely to have had an incentive to coordinate implicitly and the means to do so (fully transparent jump bids, low revenue equilibrium), some kind of signalling via jump bidding could theoretically be expected from independent, rational bidders. In this sense, implicit coordination provides a plausible framework for one possible interpretation of bid patterns.

Summing up, what the first-round bid patterns clearly suggest (and what the final auction outcome confirmed) is that none of the three allegedly strong bidders, T-Mobile, Vodafone and O2, was willing to make room at the 800 MHz band. The key determinant of the path of play is now the response by E-Plus.

4. Bidding for Bargaining Power: The Allegedly Weakest Bidder

Following our analysis, E-Plus has three options to respond to the supposed message sent by the jump bids at 800 MHz of the three competitors. First, E-Plus can straightforwardly bid on two digital dividend blocks up to valuations. This might imply a price war that the allegedly weakest bidder, E-Plus, was probably unlikely to win.

Second, E-Plus can reduce demand at 800 MHz to zero and thus implicitly agree to an outcome with three other winners of the digital dividend. In this scenario, other bidders might have been willing to make room for E-Plus outside 800 MHz. Indeed, they would have had a motivation to do so because according to *ex ante* predictions as well as *ex post* outcome data, E-Plus could credibly threaten to increase prices by more than €1.2 billion for each of E-Plus' competitors in case of conflict.

Third, E-Plus can try to compromise and reduce demand at 800 MHz to one block. Technically, the digital dividend involves large complementarities. While one block alone is probably not worth much, two blocks allow more profitable business cases – then, there is sufficient bandwidth to justify the significant investment in supporting the band in handsets and cell sites. This does not imply that there are also strong complementarities in strategic values, though. A bidder who wins only one block has a strong incentive to enter post-auction negotiations with the winner of the other block in order to make efficient use of the blocks. If winners then put together what they have, one block in the auction is not necessarily worth less than each of two blocks. From E-Plus's perspective, such an agreement is one of probably only two ways for E-Plus to participate in the post-auction digital dividend market. The other way would be later to merge with one of the other operators, in particular with O2. In fact, O2 (Telefónica Deutschland) made an offer of €8.55 billion to take over E-Plus from KPN in October 2013 (the competition authorities confirmed the merger in 2014). If a merger was a predictable possibility, E-Plus's efforts to acquire one 800 MHz block could possibly be justified by an attempt to improve its negotiation power in subsequent merger negotiations. (Other explanations for bidding on one block only cannot be ruled out, of course, such as raising rivals' costs and speculation. We will get back to alternatives later.)

4.1. *Network Sharing*

E-Plus decided to go for the third option, striving for an outcome with four winners of the digital dividend. In the second round, E-Plus bid for two blocks but the price bid for the second block was smaller. Following our interpretation of jump bids, this may be interpreted that E-Plus is willing to concede one block. This is what happened. In round 7, E-Plus withdrew one of the two bids at 800 MHz, making it clear that they wanted only one block.

Moreover, both second-round bids targeted the blocks that were held by O2, even though O2's blocks at that time were more than three times – more than €12 million – more expensive than the other blocks in the digital dividend that were worth at least as much. Also, the larger bid was actually on the less-valuable block A; recall that block A at 800 MHz has greater interference issues. The interpretation seems clear. E-Plus wanted O2 to make room for E-Plus to win one 800 MHz block.

As a result, there was excess demand of one block at 800 MHz. This started fierce price competition in the digital dividend band. In the course of this bidding war, E-Plus several times came back when being outbid by simultaneously bidding on three blocks. The first time this occurred was in round 24. After bidding on three blocks, E-Plus always subsequently reduced demand to one block, by withdrawing high bids at 800 MHz. These patterns might be interpreted as another powerful signal of its resolve to secure one block, as well as its willingness to drive up prices if others do not concede.

One might think that E-Plus' strategy to reduce demand by bidding on one digital dividend block only is as hopeless as bidding on two blocks because the allegedly stronger competitors may always outbid E-Plus. This is not necessarily the case though. In fact, as we show below, reducing demand creates incentives for others to also reduce demand. The result would be an implicit coordination arrangement, in which E-Plus wins one block. This focal outcome is likely favoured by E-Plus compared to the three-winner outcome suggested by public first-round bid patterns. However, we also present arguments below that may explain why O2 and the other bidders in fact did not concede.

Let us assume that the value of one 800 MHz block to E-Plus is v_E, and the value of one block to O2 is v_O. The value of two blocks to E-Plus is v_{EE}, and the value of two blocks to O2 is v_{OO}. Assume also $v_{OO} > v_{EE} > 2v_O \geq 2v_E \geq 0$. Regarding the total value of E-Plus and O2 sharing two blocks (v_{EO}), assume $v_{OO} \geq v_{EO} > v_{EE}$. We also assume that everything is commonly known.

First, we consider $v_O = v_E = 0$ and $v_{OO} = v_{EO}$. Applying the Nash bargaining solution to the post-auction negotiation, we predict an equal split of v_{EO} independent of sunk auction prices. This implies that, in the auction, E-Plus can credibly threaten to bid up to $\frac{1}{2} v_{EO}$ on one block, destroying all surplus, and so O2 should concede early, increasing the net surplus.

If $v_{OO} > v_{EO}$, efficient post-auction negotiations would then imply that E-Plus sells the block to O2. Applying the Nash bargaining solution, O2 would have to pay $\frac{1}{2} v_{OO}$ in the negotiation and so should again concede early in the auction.

Now assume $v_O > v_E \geq 0$. Applying the Nash bargaining solution, this weakens E-Plus's position in the post-auction negotiation. So, E-Plus can only expect $x < \frac{1}{2} v_{EO}$ of the surplus in the negotiations. However, this allows E-Plus to bid the price in the auction up to x per lot, meaning that, with straightforward bidding in the auction on one block, O2's overall profit is $v_{EO} - 2x$ which is smaller than the outcome from conceding and negotiating: $v_{EO} - x$. Thus, again, O2 should concede early.

We now introduce one-sided incomplete information: E-Plus does not know v_{EO} ($=v_{OO}$), but O2 does. Then, a sharing contract between O2 and E-Plus can be conditioned on actual (future) profits and so, again, all surplus (v_{EO}) would be shared equally. Because O2 knows v_{EO}, O2 will not bid above ½ v_{EO} for each lot, allowing E-Plus to bid at no risk as long as O2 bids. So, O2 should concede early. Similar arguments hold for $v_{OO} > v_{EO}$. In this setting, as would be the case with two-sided incomplete information, post-auction negotiations are not guaranteed anymore to result in an efficient assignment.

So, in all these cases, E-Plus' strategy for reducing demand should have induced O2 to also reduce demand. One reason is that in most cases described above, E-Plus can safely bid as long as O2 is bidding (or one of the other competitors drops out) – even when E-Plus does not know the competitors' maximum willingness to bid and even when E-Plus' value of one block is very small. Yet, this is not how the auction eventually played out; E-Plus conceded after a fierce price war. Indeed, O2 had good reasons to not concede, as we describe below. The resulting clash of strategies – E-Plus' demand for one unit and O2's and others' unwillingness to demand less than two units – resulted not only in high revenues but also in substantial risks to bidders and to efficiency.

Negotiations often involve costly delay, uncertainty and inefficiency as a result of private information or some other factor (Myerson and Satterthwaite, 1983; Cramton, 1984). This is especially likely to be the case if the parties are asymmetric, as is the case. At the time of the auction, O2 was allegedly stronger than E-Plus. The prospect of costly, uncertain and possibly inefficient negotiations after the auction may have contributed to O2's unwillingness to concede.

The implication of our theoretical analysis that there might be multiple equilibria in the auction and that different bidders preferred different equilibria may have contributed to the conflict in the auction by creating a 'war of attrition' or 'chicken game', which may pose risks to bidders. Indeed, during the auction on 22 April 2010, KPN released a press statement, announcing that 'KPN is determined to acquire a valuable combination of spectrum in the auction, including one block in the 800 MHz frequency band', which might be interpreted as a public commitment to stand firm at 800 MHz, which could make E-Plus's strategy in a war of attrition or chicken game more credible (Schelling, 1960). Moreover, O2 was outbid by E-Plus on one block in the digital dividend band in round 122 at a price which was already larger than €400 million per block and O2 did not come back before round 199. That time, O2 was probably considering whether to concede on one block and to rather focus on other bands. However, they finally did resume bidding on two blocks, risking again that E-Plus might be willing to match almost any bid, thereby again creating strategic risks and other challenges to bidders.

For instance, given that post-auction negotiations may not be efficient, a price war in the auction, with E-Plus bidding on one object only, created exposure problems. Bidders aiming to win a package of two blocks might end up with one block at a price which would only be justified by winning the whole package.

Another source of risk, and probably the most plausible reason for not conceding, is O2's concern that E-Plus might hold hostage some of O2's network investments in the negotiation. Network investments enhance the value of the spectrum and therefore would increase E-Plus's negotiation pay-off. E-Plus then can benefit from delay and exploit O2's eagerness to make network investments or take advantage of existing investments. Operators with many billions invested in networks should be concerned about anything that may lead to their investments being held hostage. This concern may have been enough to keep O2 from conceding.

A final source of the risk, motivating O2 not to concede, is the free-rider problem. O2 may hope that either T-Mobile or Vodafone would concede. However, given the strength and much larger market shares of T-Mobile and Vodafone, such a hope seems implausible.

4.2. *Speculation*

One alternative perspective on E-Plus's strategy is to assume that there was no intent to share networks, and that the 'use value' of one block (v_E) is small or zero. From this perspective, by bidding on one block only, E-Plus' bids like a pure speculator. In fact, the literature on speculators in multi-object auctions is related to our analysis above, and provides further support for the robustness of our analysis. According to this literature, speculators can be defined as bidders who have no or only a low use value of the relevant objects and attempt to buy only in order to later resell to bidders with a higher use value.

Pagnozzi (2010), in particular, argues that speculators often affect incentives to reduce demand of high-value bidders. He develops a simple auction model with commonly known constant marginal valuations to show that high-value bidders may strictly prefer to let speculators win some items and then buy these items in the resale market.[10] One reason is that this keeps the auction price down and that the corresponding savings can then be shared in the resale market. That is, in Pagnozzi's simple model, it is not true that speculators necessarily increase revenues. Rather, they strive for a low-price equilibrium in the auction. This leads to an inefficient auction outcome but because in his model values are common knowledge and all bidders have constant marginal valuations, the resale market eventually obtains an efficient assignment.

In our context, too, E-Plus's strategy may be understood as an attempt to move some of the trade to post-auction negotiations. Our case is complicated by the fact, however, that there are incomplete information and strong complementarities. In this context, bidding on one block induces strategic uncertainty and risks that can hamper final efficiency and affect revenues in ways that are difficult to predict. Moreover, in our

[10] This is particularly likely when bidders' valuations are sufficiently different. If in his model values are more clustered, speculators may also increase auction revenues. There can be no resale in similar models with only one object for sale in the auction, except when there is private information about values (Garratt and Tröger, 2006). See, e.g., Milgrom (1987), Haile (2000, 2003), Pagnozzi (2007), Hafalir and Krishna (2008), and Ockenfels (2009) and the references therein for more explanations why and how resale markets may arise.

model, there are multiple equilibria with the possibility of miscoordination and costly escalation of conflict, which is not considered in Pagnozzi's model.

4.3. *Relative Standing and Reciprocal Punishment*

There are potential complementary motives behind E-Plus's and others' strategies in the German 4G auction. One of the most robust and major findings in behavioural economics is that people do not like 'falling behind others', and that some people are willing to (reciprocally) punish behaviour and outcomes that are perceived as unfair or aggressive. Such concerns are found to often be a key determinant for the (in)efficiency and distribution of outcomes (Bolton and Ockenfels, 2000). This holds both for bargaining games (Güth *et al.*, 1982) and cooperation games (Fehr and Gächter, 2000), where punishment and counterpunishment in an attempt to enforce a desired outcome may yield inefficient conflict (Nikiforakis, 2008).

Maybe a concern for relative standing also contributed to E-Plus's strategy. Specifically, one additional reason why E-Plus was going for one block at 800 MHz might have been that seeing the three competitors win the digital dividend did not seem fair to E-Plus at low first-round prices but more acceptable at high last-round prices. That is, a bidding war at the digital dividend may make losing the digital dividend more acceptable to E-Plus and may make it easier for E-Plus to communicate the results within their organisations, to the public and their stakeholders. While we caution that it is difficult – if not impossible – to reveal intentions behind bidding strategies in naturally occurring field settings and that there may be other reasons behind raising rivals' costs more than own costs, evidence in behavioural research strongly suggests that such concerns cannot be simply ignored. In fact, it has been argued elsewhere that the motives and behaviour found in the laboratory with student subjects are also relevant in naturally occurring markets (Bolton *et al.*, 2013; Bolton and Ockenfels, 2014 and the references therein), among managers (Bolton *et al.*, 2012; Ockenfels *et al.*, 2015, and the references therein), and in auction contexts (Selten, 2001; Morgan *et al.*, 2003; Janssen and Karamychev, 2013). That said, we believe that there is much scope and need for more research on the role of fairness in auction design and behaviour.

The auction also saw a couple of instances of what might be interpreted as 'reciprocal punishment' of what might have been perceived as 'overly aggressive' behaviour (although here, too, other interpretations cannot be ruled out). For instance, there was no bidding in rounds 2–37 in the 1.8 GHz band. Everything seemed to be settled efficiently: bidders held those blocks that were adjacent to their already held block. But then, in round 38, O2 increased the price of the E-block at 1.8 GHz by €10 million. This block naturally complements E-Plus's already held frequency and is of no or only negligible value to O2. One possible interpretation of this behaviour is that O2 got increasingly frustrated by E-Plus's aggressive strategy and signalling, including bidding on three blocks in 800 MHz. O2 possibly wanted to send a powerful counter message that they were not going to concede at 800 MHz. E-Plus immediately responded by bidding on blocks that naturally complement O2's portfolio: block D at 1.8 GHz and block D at 2.0 GHz.

Later, in round 60, E-Plus and O2 repeated basically the same pattern. After E-Plus aggressively bid on three blocks at 800 MHz, O2 increased the price of the C-block at

2.0 GHz by a large €20 million jump. This block is adjacent to two blocks already held by E-Plus and the public data are consistent with the conjecture that O2 did not show interest in this block before. E-Plus immediately responded by bidding on the D-block, which in turn is adjacent to two blocks already held by O2. Such escalation of conflict jeopardises efficiency goals and increases prices for bidders beyond competitive prices.

A final example for a potential concern for relative pay-offs is a 'price equalisation process' in the 1.8 GHz band. At some point, partly because of the punishment strategies described above, prices for the blocks A-E significantly differed, with the blocks next to what T-Mobile already held being the least expensive. For instance, in round 124, prices for 1.8 GHz blocks ranged from €4.24 million for block B and C to €19.58 million for block E. But then, both E-Plus and O2 started bidding prices up until all blocks approximately reached the €20 million level of the highest-priced block in that band in round 153. After that, both bidders withdrew their interest in the blocks adjacent to T-Mobile's blocks, and no high bidder was outbid anymore in that band. There is no simple explanation for this specific bid pattern in standard auction theory, but it is consistent with an aversion to paying more than competitors.

5. How the Auction Played Out

In the end, it took 6 weeks (12 April to 20 May 2010) and 224 bidding rounds to resolve the conflicts. When E-Plus finally gave in (that is, did not come back after being outbid at 800 MHz in round 221), the auction ended almost immediately. Figure 2 shows the final auction assignment and prices. Auction revenues totalled €4.4 billion, which is close to the range of the €5–7 billion that some observers expected in advance assuming a competitive auction. There is no reason to suppose that, overall, the final assignment is inefficient (with one minor exception).[11] Moreover, the three allegedly strong bidders each won two blocks in the 800 MHz band, at prices around €1.2 billion. Clearly, implicit coordination at low prices failed. The costs of the bidding conflict – the failure of implicit coordination – was large. The actual price of the digital dividend for T-Mobile, Vodafone and O2 is about €1.2 billion higher, for each bidder, than what would have been the price if the conflict had been resolved after a few rounds. Under the assumption that other bidders would have made room for E-Plus outside the digital dividend if E-Plus had reduced demand at 800 MHz, E-Plus might have won the same blocks that it eventually won at a price discount of €247 million.[12]

[11] E-Plus won the D-block at 1.8 GHz, although the block likely had only negligible value to E-Plus because it is not adjacent to other spectrum of E-Plus. As we mentioned above, during the auction, the price of the D-block went up probably because of some punishment or other bidding tactics. Finally, E-Plus was the high bidder on the D-block but withdrew its leading bid in round 156. Yet, O2 did not come back, although O2 owns adjacent blocks, indicating that they were not interested anymore in this block at this price. So, in round 188, E-Plus came back and regained the status of the high bidder on the D-block. Thereafter, no other bidder showed any interest in this block. If E-Plus had not bid again on the D-block they would have had to pay their withdrawn bid for the block but not receive it. So, given that nobody was interested anymore when E-Plus withdrew its bid, coming back was a rational strategy.

[12] The only exception is the D-block at 1.8 GHz, where E-Plus at best had little interest; see previous footnote.

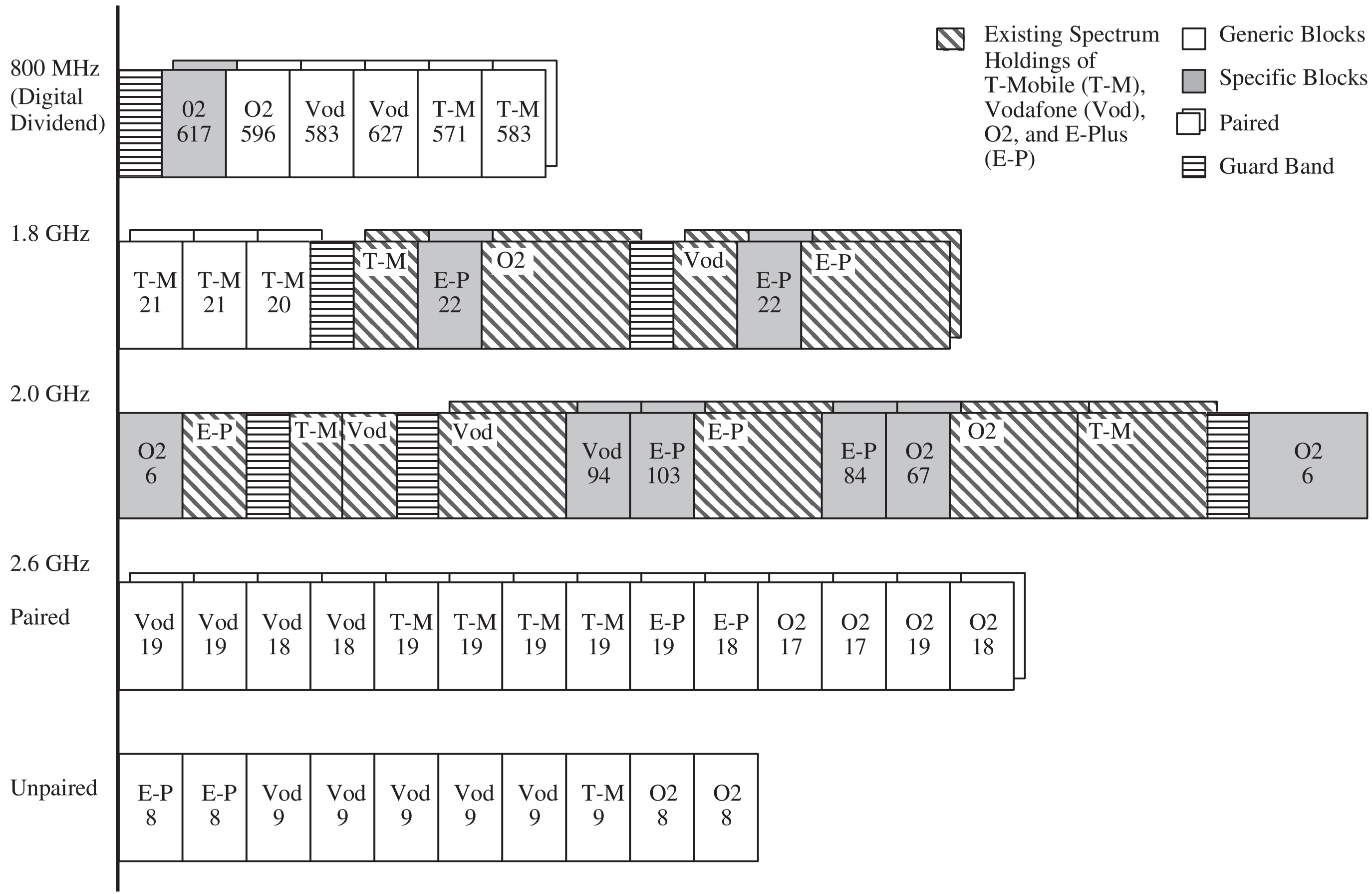

Fig. 2. *Final Auction Outcome (Assignment and Prices in Million €)*
Note. The Figure shows the final specific assignment of all blocks, including of the generic blocks.

6. Augmenting the Simultaneous Ascending Auction Format

There is no perfect auction format. Any auction has advantages and disadvantages and each spectrum auction design must be tailored around the specific context it is designed for. The chief advantage of the German 4G auction design is that it is simple and well tested. By 2010, much experience had been gained on the simultaneous ascending auction. The design generally performed well and was well understood by the bidders. This was also the case in Germany.

However, some design details seem to have made the German 4G auction version of the simultaneous ascending auction vulnerable to strategic behaviour. This vulnerability can increase risks for all stakeholders. These concerns can be addressed by rather minor changes, without changing the essentials of the simultaneous ascending auction format.

Most importantly, the transparent information feedback in Germany's 4G auction may facilitate implicit coordination (Cramton and Schwartz, 2002; see for a similar discussion of the role of transparency in the context of gasoline prices in Germany, Haucap and Müller, 2012) as well as punishment and other costly 'communication through bidding' tactics. We recommend abandoning full transparency and instead only report, say, aggregate demands at the end of each bidding round. This tends to mitigate the scope of implicit coordination, as well as 'communication through bidding' tactics that may hurt bidders and efficiency.[13]

Further, one may make greater use of generic lots to enhance substitution and simplify the auction. Having specific (versus generic) blocks at 1.8 and 2.0 GHz extends the scope for strategic gaming, and in particular, for targeted punishments. Such bidding patterns can increase bidder risks and distort efficiency because they tend to favour less vulnerable bidders, and not necessarily the efficient bidders (see Pagnozzi, 2010 and our analysis above). Specific blocks also slow down or distort price discovery (e.g. through punishment tactics). An alternative design within the simultaneous ascending auction format would define all blocks within a band to be generic (it could be combined with the commitment of arranging contiguous spectrum blocks per band for the successful bidders after the auction). This simplifies the auction and reduces the vulnerability of bidders and thus the scope for strategic bidding.

One could also have reduced the potential gains from implicit coordination and the scope for gaming by establishing a reserve price, especially for the 800 MHz blocks, that was closer to price and market-adjusted benchmarks taken from former auctions of comparable spectrum. However, it is important for the regulator not to set a reserve price that is too high, leading to unsold spectrum, as occurred in the recent Australian 4G auction.

The essential needs option was a good idea to effectively protect an entrant against the risk of getting less than the minimum required to get a new business plan running. The option is attractive for an entrant because essential needs give entrants a market exit strategy. For the actual bidders, the most important complementarity was likely in

[13] However, Bichler *et al.* (2016) argue in the context of Germany's recent 5G auction that there may be a positive effect of greater transparency to help bidders express allocative externalities.

the digital dividend. Here, defining 2×5 MHz units created strategic risks to bidders because this way, the number of winners at 800 MHz was endogenous (2, 3 or 4). While this allows all bidders to win something in the digital dividend, two winners would imply a suboptimal market structure and four winners would imply post-auction negotiations, which in turn risks inefficiency and bidder exposures. These issues can be avoided by auctioning blocks of 2×10 MHz.

Some countries have adopted the combinatorial clock auction that allows bidders to bid on packages of lots and thereby eliminate the exposure problem (Ausubel *et al.*, 2006; Cramton, 2013). This might have benefits when complementarities are strong and differ among bidders. However, we caution that this also makes for a much more complex auction and poses various other challenges (Day and Milgrom, 2008; Knapek and Wambach, 2012; Janssen and Karamychev, 2013; Ausubel and Baranov, 2014). It seems that, in the German 4G auction, the relevant exposure problems could be satisfactorily taken care of with the 'essential needs' option (in case of entrants) and appropriate product design as sketched above. So, overall, the simultaneous ascending auction format was an appropriate choice, yet some design details posed avoidable risks.

7. Conclusion

Germany's 4G auction yielded an efficient outcome at reasonable prices, allowing all participating mobile operators to double their spectrum resources. We applied scenario analyses based on both, the theory of independent and rational bidding as well as on our interpretation of the bid data, to investigate potential strategies in the auction. We show that our scenarios are consistent with the view that an outcome with four winners of the digital dividend and a revenue at about only 2% of actual revenue might have been in reach – although we cannot rule out other interpretations of the bid strategies. Our scenario analyses also suggest E-Plus's strategy of reducing demand to only one 800 MHz block (although one single block likely has limited value) was due to an attempt to improve post-auction negotiation power and imposed strategic uncertainties and risks to competitors, auction revenues and efficiency.[14]

Mitigating some of those risks seems desirable. The simultaneous ascending auction format is flexible enough and can be further developed to address the challenges that we identified in the German 4G auction satisfactorily. In addition, the German 4G auction highlights the need to better understand focal points, fairness considerations and the important role of speculators in situations in which lots are complements.

[14] Post-auction negotiation issues are also coming up in other auctions, such as the 2014 New Zealand auction. In this case, there were three incumbents, one large and two small. To compete with the large carrier, the two small ones contemplate a network sharing arrangement before the auction. The regulator conducts a clock auction for generic blocks followed by a combinatorial assignment stage to determine specific assignments. Notice that the two small carriers have a strong interest in being adjacent to improve the efficiency of network sharing. In contrast, Telecom wants to be in the middle, reducing the efficiency of network sharing and harming competition. In this case, the regulator should have prevented Telecom from expressing a preference for middle. But, it did not. In the end, the two small bidders pushed the large one off to the ends. In Germany, the negotiated assignment stage would always put the big operator on one of the ends, since efficiency was the deciding factor in case of disagreement.

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