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Geoffrey Myers[1]

Abstract

The approach to competition issues in the UK 4G spectrum auction involved the innovative use of spectrum floors, i.e. the flexible reservation of portfolios of spectrum for either a new entrant or the smallest incumbent national mobile competitor (H3G). This measure emphasised output efficiency through promoting downstream competition and its implementation in the auction sought also to maximise auction efficiency (subject to the constraint of the floor) through sophisticated modifications to the already complex design of the combinatorial clock auction. Whilst the full scope of this new regulatory tool was not tested in the 4G auction, the evidence from the outcome and the bids showed how the market information in auction bids was used to choose the spectrum to be reserved as the floor which maximised the incremental value in the bids of the beneficiary net of the opportunity cost to other bidders. The use of spectrum floors led to a surprising outcome since H3G won a floor of highly valued, scarce sub-1GHz spectrum in the 800MHz band, but this reflected the consistent pattern of bids in the auction, in particular by EE and H3G itself.

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A. Introduction

> *Policies that increase competition and permit wireless markets to operate more efficiently empirically dominate social gains from license rent extraction.*
>
> (Hazlett and Muñoz 2009: 437)

Radio spectrum is the range of frequencies over which radiocommunication is possible, which in turn is the transmission of information by means of radio waves. Spectrum is a fungible input used to supply a very wide range of downstream services. One of the highest value uses is cellular mobile services. In the UK in 2012 there were almost 83 million mobile connections (considerably more than the population of the UK), revenue from mobile voice and data services was £15.3 billion (Ofcom 2013c: Figs. 5.26, 5.22) and consumer surplus from such services has been roughly estimated at £24 billion per annum.[2]

Ownership of smartphones and tablets is growing quickly. Such mobile devices are increasingly being used for a wide range of data services, including internet surfing, social networks, listening to music, and watching videos. This is associated with rapid growth in mobile data traffic, e.g. more than a doubling between 2011 and 2012 (Ofcom 2012d: Fig 21), with a fast rate of growth expected to continue for many years.

Spectrum is an essential input into mobile services, enabling the mobility of communications which consumers clearly value highly. Most of the spectrum used for mobile services is available via individual licences, i.e. a single licensee that has the right to use the specified frequencies free from harmful interference.[3] Given their centrality to mobile operators' businesses and their scarcity, licences to use spectrum frequencies are key assets in the value chain for mobile services.

The 4G spectrum[4] auction in the UK, which took place in January and February 2013, was played for high stakes. Firstly, there was a large amount of spectrum available in the auction (250MHz) and it was valuable. Some of the spectrum licences being sold were for the 800MHz band at a low frequency (ie sub-1GHz) which is especially scarce. The 800MHz band was formerly used for analogue terrestrial broadcasting and was released by the switchover to digital TV – hence this is the "digital dividend" spectrum. This was of high value because of the coverage advantages of such low-frequency spectrum, both in reducing the cost of providing network coverage outdoors (since radio signals at lower frequencies travel further) and in improving the quality of coverage indoors (as the signals generally

[2] Ofcom (2012a), paragraph 2.68 in Annex 6.

[3] If two operators transmit radio signals in the same frequency at the same location they interfere with each other. Individual licences provide one way of managing such interference. Another way that is adopted in other bands is through unlicensed spectrum with restrictions on the transmission power of the permitted radio equipment to limit the range of the radio signals (a key example being the spectrum used for WiFi, e.g. in the 2.4GHz band). But this means that unlicensed spectrum is generally not effective in providing the wide-area coverage that is needed for national networks.

[4] For the purposes of this paper "4G" is used to refer to mobile technologies such as Long Term Evolution (LTE). Such technologies can be deployed in a range of frequency bands, including those in the 2013 auction, but also in bands not included in the auction, such as 900MHz, 2100MHz and 1800MHz in which the UK's first 4G network was deployed by Everything Everywhere in late 2012. However, we use the label "4G auction" for convenience.

penetrate inside buildings more effectively). The other spectrum in the 4G auction at the higher frequency of 2.6GHz did not have such coverage advantages and so was significantly less valuable,[5] but still important in providing additional spectrum capacity to meet the fast-growing demand for mobile data.

Secondly, the spectrum being sold represented a large increase (about 70%) on the pre-existing spectrum used for mobile services, taking it from about 350MHz to 600MHz (see Figure 1 in Section B for further details of the relevant bands). Thirdly, future releases of other spectrum suitable for mobile services were either at an uncertain time in the future (eg 700MHz) or at higher, less attractive frequencies (eg 3.4GHz). Fourth, an implication of the preceding features is that the pattern of spectrum acquisition would influence the market structure and future competitive intensity for many years in the relevant downstream markets for mobile services, especially mobile data and broadband.

Spectrum floors

For major spectrum auctions with the potential of long-lasting effects on competition, such as the UK 4G auction, it is relevant for the regulator to consider the nature of any competition concerns and the case for imposing competition measures to address them. Ofcom, the UK communications regulator, decided to impose different competition measures to address distinct competition concerns:

(a) Spectrum floors, an innovative competition measure providing the flexible reservation of spectrum for new entrants or the smallest incumbent, to promote downstream mobile competition between at least 4 national mobile competitors; and
(b) Spectrum caps to avoid highly asymmetric post-auction distributions of spectrum.

The focus of this paper is on the competition measure of spectrum floors: their rationale to achieve the stated competition objective compared to traditional measures, the way they were implemented, and the outcome in the auction.

The traditional approach to competition measures in auctions is to use spectrum caps or simple spectrum reservation (set-aside). Caps place a limit on the maximum amount of spectrum any mobile operator can acquire. Set-aside is spectrum for which only a defined class of bidder can compete, such as small incumbents or new entrants. Such competition measures can be characterised as providing a remedy to the risk of market failure, i.e. that small incumbents or new entrants fail to acquire the spectrum which they need to be effective competitors so that the market mechanism of the auction fails by resulting in a weakening of downstream competition to the detriment of consumers.

But these measures can also give rise to a significant risk of regulatory failure. Caps may prevent larger incumbents from acquiring spectrum even if they are the highest-value users of this scarce resource. Through set-aside the regulator might choose the wrong spectrum to reserve, failing to maximise the benefit of reservation net of opportunity costs. This is a particular concern if there is a range of different portfolios of reserved spectrum that could similarly achieve the objective of promoting downstream competition.

[5] The auction prices suggested that spectrum in the 800MHz band was valued about five times more per MHz than in the 2.6GHz band.

The risks of market and regulatory failure were highly relevant to the 4G auction. The new competition measure of spectrum floors sought to reduce the regulatory failure problems whilst still addressing the risk of market failure and promoting competition. Spectrum floors have two dimensions of flexibility compared to set-aside:

(a) Different portfolios of spectrum ("floors") can be reserved for different players, e.g. depending on their different pre-auction spectrum holdings as between a new entrant or the smallest incumbent (H3G); and

(b) The choice of spectrum to be reserved from a range of floors, each of which is sufficient to promote competition, is decided through the auction as the floor that maximises the net benefit of spectrum reservation, taking into account the valuations of the different spectrum floors by both the:
   (i) beneficiary of the reserved spectrum – its incremental differences in bid values between the different floors; and
   (ii) other bidders – the opportunity cost expressed in their bids of being denied the ability to acquire the reserved spectrum.

Spectrum floors thus involve an auction for reserved spectrum within the wider auction for the entirety of the spectrum on offer, and competition between the sub-auctions determines the specific floor of spectrum that is ultimately reserved. As such, a key and innovative advantage of spectrum floors is that it makes use of *market information* to decide the specific spectrum frequencies to be reserved rather than the regulator's judgement (as with set-aside). The regulator may be well intentioned but it has less information compared to market participants on the value and opportunity cost of different spectrum frequencies, so that using market information avoids the material risk of regulatory failure, i.e. the regulator deciding to reserve the wrong spectrum portfolio (given the different net benefits of reservation of the different portfolios).

Section B in this paper discusses in more detail the rationale for spectrum floors and the potential advantages over the traditional remedies. Section C sets out the implementation of the 'auction within an auction' for spectrum floors in Ofcom's chosen auction format, the combinatorial clock auction (CCA).[6]

[6] There are a number of differences from auctions used by regulators in other industries, which include the sale of franchises, such as for rail services or bus routes, or procurement, such as electricity generation or universal service obligations in telecommunications. Firstly, spectrum auctions are for the sale of licences to be used by the purchasers as an *input* in their supply of services in downstream output markets (such as mobile data), whereas the items for sale in these franchise auctions are for the right to provide defined services in the output market, or in the procurement auctions the regulator is purchasing (or facilitating the purchase of) services from suppliers. Secondly, because spectrum auctions are for inputs, there is the potential for alternative mixes of the items for sale (i.e. alternative spectrum portfolios) to be sufficient to enable the purchaser to be an effective competitor in the same services in the downstream output market. Thirdly, in spectrum auctions some of the items for sale may be reserved or set aside for new entrants or small incumbents to promote downstream competition. Fourthly, building on these latter two points, the new regulatory tool of spectrum floors can provide flexible reservation in two dimensions with bids in the auction deciding both: (a) which of the eligible bidders is the winner of the reserved spectrum (where the floors may differ between different eligible bidders); and (b) which specific set of frequencies is reserved, i.e. the winning floor from a choice of portfolios.

The actual bidding in the 4G auction is analysed in Section D, focusing on the selection of the winning floor which turned out to be a small block of spectrum (2x5MHz)[7] in the high-value 800MHz band instead of the alternative floor of a larger amount of spectrum (2x20MHz) in the 2.6GHz band. This came as a surprise to some, but it reflected the consistent pattern of bids in the auction, thereby illustrating the relevance of the innovative flexibility in spectrum floors. The bids made in the auction expressed a higher incremental value to the beneficiary (H3G) of the floor of 800MHz spectrum (£165m) than the opportunity cost to other bidders (£107m). H3G bid incremental values for its spectrum floors equal to the difference in their reserve prices, which ensured that whichever spectrum floor it won it would only pay the reserve price. The overall opportunity cost of the floor of 800MHz spectrum to the other bidders was reduced by the bids made by one of them, EE, which expressed a negative incremental value (for 2x5MHz of 800MHz compared to 2x20MHz of 2.6GHz).

Auction and output efficiency

As an overarching framework, we distinguish three types of efficiency:

(a) *Auction efficiency* occurs if the spectrum is acquired by the highest-value bidders;
(b) *Output efficiency* occurs if the allocation of spectrum in the auction is such that it maximises the incremental gain in allocative, productive and dynamic efficiency in output markets, in this case downstream mobile markets; and
(c) *Public financing efficiency* occurs if the least distortionary method is used to raise public funds.

In this context the important implication of spectrum being an intermediate input is that auction efficiency does not necessarily further overall economic efficiency, which depends instead on output and public financing efficiency. The value of bidders in an auction for spectrum depends on their expected profit (specifically, the difference in profit with and without the spectrum) and there can be a divergence between the activities in output markets for which spectrum is used that are the most profitable and those that generate the greatest social benefit (see Borenstein 1988).

We also distinguish two sources of profit or value for a bidder:

(a) value in the absence of intentions to reduce competition in output markets, which is referred to in Ofcom (2012a,b) as "intrinsic" value;[8] and
(b) "strategic investment" value, i.e. returns to the bidder from using spectrum purchases to deny spectrum to downstream competitors and thereby foreclose or restrict competition in output markets.[9]

[7] 2x5MHz indicates paired spectrum, i.e. a 5MHz carrier in the downlink for the customer to receive data to the mobile device from the base station in one frequency and another 5MHz carrier in a different frequency in the uplink to carry data sent from the mobile device to the base station.

[8] In turn, intrinsic value is sometimes decomposed into cost savings and commercial value. Cost savings may arise from spectrum that is suitable for deploying the latest, most spectrally (or productively) efficient technology, or is in lower-frequency bands such as 800MHz which require fewer base stations to provide a given coverage, thereby allowing savings in network costs. Commercial value may arise from increases in the functionality or quality of the downstream mobile services that can be offered, such as faster download speeds, and consequent gains in price premia, etc.

[9] Intrinsic value and strategic investment value are referred to in Cramton et al. (2007) as "economic value" and "foreclosure value", respectively.

For the purposes of this paper we define auction efficiency as relating both to bidders' intrinsic and strategic investment values. The inclusion of strategic investment value in this definition assists in sharpening the distinction we draw between auction efficiency and output efficiency. If a bidder wins spectrum only because of its strategic investment value, this might further auction efficiency but be undesirable for output efficiency through foreclosure of competition in the downstream market.

We use the term "strategic bidding" to refer to deviations from a bidder's intrinsic value. An example is strategic demand reduction, where a bidder restricts its demand in an auction with uniform prices to reduce the price it pays for the inframarginal units of spectrum it does win.[10] Alternatively, strategic bidding reflecting strategic investment value could be to affect the conditions of competition in the output market.

There is a distinction between these two types of strategic behaviour, although both are generally undesirable for efficiency. Strategic demand reduction involves *reducing* demand for spectrum to reduce competition in the *auction* and thereby lower the auction price, which reduces auction efficiency. However, strategic investment involves a bidder *increasing* demand for spectrum to reduce or distort competition in *output* markets, which reduces output efficiency. As set out in Section C, the design of the auction seeks to provide incentives for truthful bidding which alleviates strategic demand reduction. The incentives for strategic investment are mitigated by the competition measure of spectrum floors explained in Section B.

In general, spectrum auctions can further public financing efficiency because they may be a more efficient way to raise public funds than general taxation. The welfare costs of taxation, i.e. the deadweight losses caused, have been estimated at between 15 and 50 cents for each $1 of tax for an economy like the United States (see Ballard, Shoven and Whalley 1985). In principle, revenue from spectrum auctions can avoid any distortion of output because the direction of causation is that auction bids are determined *by* the expected future profit from the pattern of output using the spectrum in question (rather than output decisions being determined by the price paid for spectrum in the auction).

As regards the relationship between output and public financing efficiency, there is growing recognition that, whilst the amount of revenue raised by an auction is the dominant theme in news reporting of spectrum auctions and maximising seller revenues is a key point of interest in the auction literature, the impact on downstream markets is usually more important to overall efficiency, e.g. see Klemperer (2002), Hazlett and Muñoz (2009), and Cramton et al. (2011). Although in general their relative importance depends on circumstances, it is argued in Hazlett et al. (2012) that output efficiency is very likely to dominate any public financing efficiencies in spectrum auctions.

[10] As set out in Ausubel and Cramton (2002), this is analogous to the profit-maximising choice of a monopolist (in the absence of price discrimination) to restrict output and set a monopoly price – it sells less output (buys less spectrum) but this is more than offset by the larger profit margin on its inframarginal sales (spectrum purchases).

However, in the context of the UK such a debate was moot. Ofcom's statutory duties include furthering the interests of consumers, where appropriate through the promotion of competition, and optimal use of spectrum. These can be seen as relating to output and auction efficiency. But as regards public financing efficiency, Ofcom has no duty to raise revenue. Therefore, in this paper we do not discuss public financing efficiency in any detail.

Instead our focus is, firstly, in Section B on output efficiency in the rationale for imposing spectrum floors. In the right circumstances, as in the UK 4G auction, spectrum floors provide a better way to balance market and regulatory failures when promoting mobile competition through the auction than the traditional competition measures (caps, set-aside or bidder credits).

Secondly, in Section C we consider auction efficiency in setting out how spectrum floors were implemented in the auction format (CCA). Spectrum floors seek to harness auction efficiency (subject to the constraint that spectrum is reserved) to further output efficiency through promoting downstream mobile competition. In making sophisticated modifications to the already complex design of the CCA to implement floors, the intention was to preserve desirable incentives for truthful bidding, so that the auction would indeed reveal the winning spectrum floor as the one that maximised the net benefit of reservation.

Thirdly, the bids made and the outcomes from the UK 4G auction are considered in Section D, focusing on the winning floor – which came as a surprise – and the reasons for its choice in the auction. We assess both aspects of the net benefit of reservation: the preferences and bidding strategy of H3G, the operator that benefited from spectrum reservation, and the opportunity cost to other bidders that were denied the opportunity to acquire the reserved spectrum. Finally, the conclusions are set out in Section E. An evaluation of the success of spectrum floors in terms of output efficiency is beyond the scope of this paper (and in any case it is too soon to assess either the effectiveness in promoting mobile competition or the impact on consumers). As regards auction efficiency we consider the circumstances in which the market information of bids in the auction led to the efficient choice of spectrum floor to be reserved.

B. Purpose and rationale of spectrum floors

> *In some auctions, for example of mobile-phone licenses, the structure of the industry that will be created cannot be ignored by the auction designer.*
>
> Klemperer (2002: 177)

The different competitive position in the relevant output market of firms that are bidding against each other in an auction can be an important source of divergence between auction efficiency and output efficiency. As explained in Cramton et al. (2007: 4):

> This is the great deficiency of an unrestricted auction when incumbents have rents to protect. Symmetric auctions among asymmetric bidders are prone to

> inefficient outcomes because the interests of consumers are not directly represented in the auction – the responsibility to promote consumers' interests resides with the FCC and the Division [ie the US sector regulator and competition authority] when they consider the rules of the auction and the awarding of licenses in the public interest. Both those decisions will inevitably shape the structure of the industry far into the future.

This is why, in major spectrum auctions, selling to the highest bidder may adversely affect output efficiency through weakening downstream competition. So the regulator should consider whether and what competition measures should be imposed in the auction to promote competition.

In designing the 4G auction, Ofcom conducted a detailed assessment of the impact on competition in downstream output markets and developed a specific objective to promote competition, via the auction, between at least four national mobile operators. It is beyond the scope of this paper to assess the appropriateness of this competition objective – instead the focus is to analyse the new regulatory tool of spectrum floors used to achieve it. In this section we outline the rationale for spectrum floors and the relationship to auction and output efficiency.[11]

Ofcom (2012a, b) conducted the following analytical steps which we discuss in turn below:

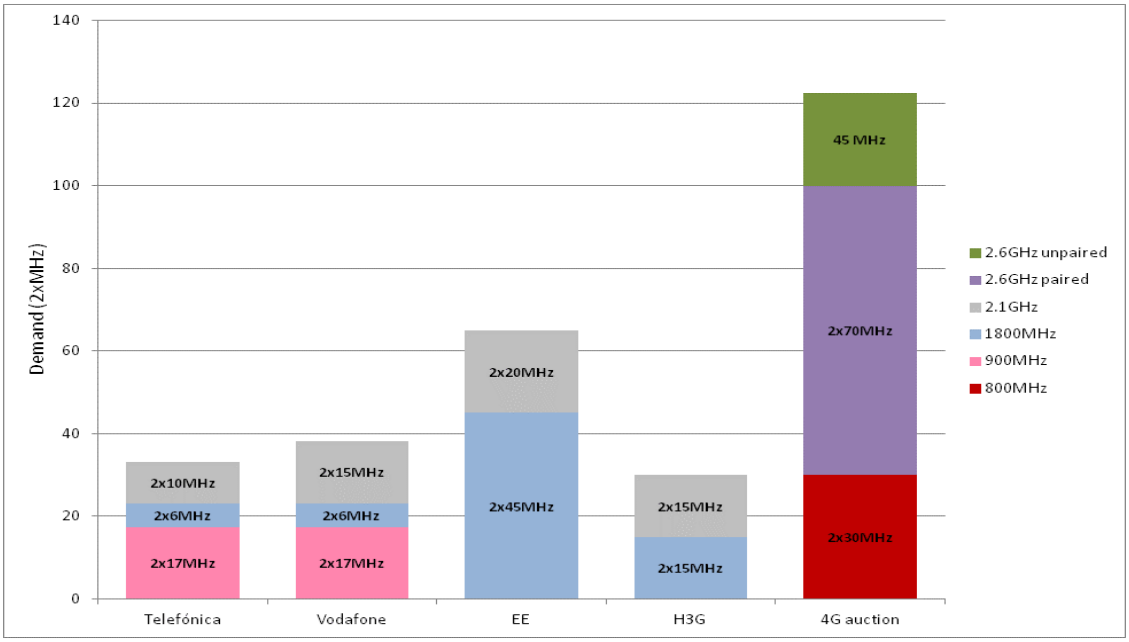
(a) Firstly, assess the extent to which the strength of downstream competition after the auction depends on various current and potential future competitors acquiring *spectrum* in the auction;
(b) Secondly, analyse the *market failure* risk that these competitors will fail to acquire such spectrum in the auction;[12] and
(c) Thirdly, consider *competition measures* to alleviate such concerns, especially spectrum floors, taking account of the risk of regulatory failure.

Spectrum requirements for strength of downstream competition

Ofcom concluded that it was important to maintain at least the pre-auction market structure of four national mobile competitors to promote competition to the benefit of consumers. The pre-auction spectrum holdings are shown in Figure 1 alongside the spectrum in the 4G auction. To remain effective competitive forces in the market, Ofcom concluded that the three larger incumbents – Everything Everywhere (EE), Vodafone and Telefónica (which uses the brand name "O_2") – either needed no or little spectrum in the 4G auction to have at least the minimum holdings to be capable of remaining effective competitors (even if more spectrum might enhance their competitive positions). For EE, this was primarily because of the size of its pre-auction spectrum holdings; whilst for Telefónica and Vodafone another important consideration was the greater value of their pre-auction holdings of sub-1GHz spectrum in the 900MHz band (i.e. low-frequency spectrum which provides network cost savings or quality of coverage advantages because the signals travel further).

[11] Further details are set out in Section 4 and Annexes 1 to 2 of Ofcom (2012b).
[12] This is a market failure risk relating to output efficiency. There are other potential sources of market failure relevant to auction efficiency such as asymmetric information and market power.

Figure 1: Pre-auction spectrum holdings by operator and spectrum in 4G auction



Source: Author from Ofcom (2012b), Table 4.1

But Ofcom concluded that H3G (which uses the brand name "3"), the smallest incumbent in terms of spectrum holdings (and market share) and without any sub-1GHz spectrum, needed to acquire spectrum in the auction to be capable of remaining an effective constraint on its rivals. Any new entrant would also need to acquire spectrum to be capable of having a significant impact on competition at the wholesale level. Mobile Virtual Network Operators (MVNOs), such as Virgin Mobile and Tesco Mobile, affect retail competition but they are reliant on wholesale access from national mobile operators. As a result they do not provide competition at the wholesale level which is especially critical to underpin the strength of competition benefiting retail consumers, both directly via vertically integrated operators and indirectly via wholesale access provided to other retail suppliers such as MVNOs. Ofcom (2012a, b) emphasised the importance of competition between "national wholesalers". This suggested that output efficiency would be enhanced by sufficient of the spectrum in the 4G auction being acquired by H3G or a new entrant.

Given different characteristics of different frequency bands and spectrum amounts, which constitute a complex mix of substitutes and complements, Ofcom concluded that downstream competition and output efficiency would be promoted by H3G or a new entrant acquiring *any one* of the spectrum portfolios shown in Figure 2. The applicable portfolios in the 4G auction differed between H3G and a new entrant, because of their different pre-auction spectrum holdings.

Figure 2: Alternative spectrum portfolios required by H3G or new entrant to support downstream competition

Portfolio	800 MHz	1800 MHz	2600 MHz	Reserve price
Portfolios for H3G				
(i)	2x5 MHz			£225m
(ii)			2x20 MHz	£ 60m
Portfolios for new entrant				
(iii)	2x15 MHz			£675m
(iv)	2x10 MHz		2x10 MHz	£480m

Source: Ofcom (2012b), Figs. 4.13 and 4.14

Market failure risks

If H3G or a new entrant needed spectrum in the 4G auction, they had the opportunity to buy it in competition against other bidders, including the three largest incumbents. But there are risks of market failure, i.e. reasons why H3G or a new entrant might fail to acquire the required spectrum despite it being desirable for output efficiency:

(a) Asymmetries between bidders' private intrinsic values which do not take account of competition externalities (i.e. benefits to consumers from increased competition), and so their ranking is misaligned with the ranking of their incremental effect on social value; and
(b) Strategic investment value causing incentives for the three largest incumbents to engage in strategic investment in the auction to foreclose downstream competition.

On grounds of a priori reasoning we can identify the potential for competition externalities to drive a wedge between the rankings of private and social value by bidders in the 4G auction and the potential for strategic investment. But there are various offsetting effects which make it a complex empirical question how serious these risks were in practice. Ofcom (2012a, b) assessed the available evidence and concluded that there was a material risk of a market failure due to asymmetries in intrinsic value and that the risk of strategic investment was realistic.[13]

Competition measure of spectrum floors compared to alternatives

We now consider the most effective and efficient competition measures to address the risks of market failure. This may involve a deliberate departure from auction efficiency to increase output efficiency. In any analysis of remedies it is important to take account of the potential for regulatory failure. Two general categories of regulatory failure are not fully achieving the desired objective and unintended consequences.

If the concern is that the auction bids of H3G or new entrants are too low from the perspective of output efficiency, a logical competition measure is to use bidder credits to inflate those bids to internalise the competition externalities and/or to make strategic investment too costly to be profitable. But determining the size of the bidder credit in practice

[13] See Section 5 in Annex 6 of Ofcom (2012a) and Section 4 and Annex 3 in Ofcom (2012b).

is very difficult and prone to substantial regulatory failure. Setting the bidder credit too low would fail to achieve the desired objective of correcting the market failures. Setting it too high might, in effect, pre-determine the outcome of the auction and over correct such that H3G or new entrants acquired too much spectrum with the unintended consequence that the three largest incumbents acquired too little for output efficiency.[14]

A commonly used regulatory tool in spectrum auctions is a cap, either on the amount of the spectrum in the auction that a bidder is permitted to acquire or the total post-auction holdings (i.e. acquisition in the auction plus pre-auction spectrum holdings). In 4G auctions in other European countries, spectrum caps were commonly used.[15] However, there were three related problems with caps to correct the market failures in the UK 4G auction. Firstly, caps only provide an indirect method to achieve the desired objective of a fourth national wholesaler being able to acquire sufficient spectrum in the auction. Whilst they could be used to restrict the amount of spectrum the three largest incumbents could acquire, it is only by fine-tuning the level of the caps relative to the available spectrum that it would guarantee enough spectrum of the right type for a fourth national wholesaler. Secondly, given the large asymmetries by frequency band in existing spectrum holdings in the UK (see Figure 1), caps would have needed to be particularly restrictive to achieve this and likely to damage output efficiency. Thirdly, caps would not recognise the different minimum spectrum acquisition requirements of different types of smaller competitor – see the different required spectrum portfolios for H3G and new entrants in Figure 2.

Spectrum reservation avoids some of these problems. A simple example is set-aside, i.e. specified frequencies being reserved for a defined class of bidder. Such an approach was used in the UK 3G auction in 2000 (for the 2.1GHz band): 2x15MHz was set aside for a new entrant,[16] and it was acquired by H3G. This approach works well if: (a) it is known what specific spectrum the new or smaller competitor needs; and (b) the potential beneficiaries all need the same spectrum. However, that was not case for the 4G auction. Ofcom identified a range of spectrum portfolios that would support downstream competition. Also, the spectrum required to be a fourth national wholesaler differed between H3G and new entrants. There is a benefit, therefore, in allowing bidding in the auction to determine which of the floors of reserved spectrum is acquired by H3G or a new entrant and which spectrum is acquired by the three largest incumbents. So long as a fourth national wholesaler (i.e. one of H3G or a new entrant) is guaranteed to win enough spectrum to be capable of exerting an effective constraint on its rivals in downstream markets, incentives for strategic investment are mitigated and there may be a reasonable alignment between the ranking of bidders' private values and social value.

For this to apply, any one of the floor portfolios in Figure 2 must be sufficient to support downstream competition. Otherwise there is scope for strategic bidding by the three largest

[14] It is possible to characterise spectrum floors as providing a credit to eligible bidders, although whereas bidder credits are typically determined exogenously before the auction, spectrum floors involve a credit that is determined endogenously in the auction (and is sufficiently high so that an eligible bidder wins a portfolio of reserved spectrum).
[15] See Annex 2 in Ofcom (2012b). The use of caps is also discussed in Cave (2010).
[16] All bidders other than the four incumbent mobile operators at the time (O_2, Orange, T-Mobile and Vodafone). Nine new entrants competed in the auction (see Binmore and Klemperer 2002).

incumbents to confine the fourth national wholesaler to the 'weak' portfolio thereby softening downstream competition. This was a contentious issue, in particular whether all portfolios should include at least 2x10MHz of spectrum in the 800MHz band, i.e. a significant block of spectrum in the highest-value band in the auction to provide greater network cost or quality of coverage advantages of low-frequency spectrum. We return to this question in Section D in the light of the evidence of the bids made in the auction.

The rationale for spectrum floors, therefore, is that they provide a flexible remedy and alleviate regulatory failure when imposing competition measures to address the identified risks of market failure. They reserve spectrum for a fourth national wholesaler but the reservation may differ between the candidates (i.e. H3G and new entrants) and the auction determines the identity of that competitor and which specific portfolio of frequencies is reserved, maximising the net benefit of reservation. This is achieved by taking account of both the preferences of those bidding for the reserved spectrum and the opportunity cost to other bidders of being denied such spectrum. The operation of the auction to achieve auction efficiency, subject to the constraint that spectrum is reserved for a fourth national wholesaler, is thus harnessed to promote output efficiency.

Note that as well as floors, i.e. a *minimum* amount of spectrum that one bidder (in a defined category) was guaranteed to win, Ofcom also separately imposed spectrum caps on holdings of sub-1GHz and total spectrum, i.e. limits on the *maximum* amount of spectrum that any bidder was permitted to win. Caps were assessed by reference to pre-auction holdings as well as spectrum acquired in the auction. The caps were set at safeguard levels to avoid highly asymmetric outcomes, not to guarantee spectrum for a fourth national wholesaler, and they had an effect on the auction independent of the floors. Sub-1GHz holdings were limited to 2x27.5MHz. This applied to all bidders, but in particular it constrained each of Telefónica and Vodafone to acquire no more than 2x10MHz of 800MHz in the auction. Total spectrum holdings for each bidder were limited to 2x105MHz – in particular this constrained EE to acquire no more than 2x40MHz of spectrum in the auction. In essence, the three large incumbents were not eligible to compete for the reserved spectrum in the floors and were constrained in the maximum amount of unreserved spectrum they could bid for because of the caps. Given the bidding and outcome of the 4G auction, discussed in Section D, the caps seemed to have a binding effect on these bidders and so may have been important in influencing the outcome of the 4G auction alongside spectrum floors.[17]

Spectrum floors were an innovation in regulatory design. They had never been used before in a spectrum auction. Next we discuss how they were implemented, and thereafter we assess the outcome of the 4G auction, especially the choice of winning spectrum floor.

[17] Spectrum floors can be implemented without spectrum caps. With both being used in the 4G auction, the caps could have affected the choice of winning floor to the beneficiary through their effect on the opportunity cost to other bidders of one floor compared to another (see Section D).

C. Implementation of floors in the auction

> *Auctions are fundamentally about allocating and pricing scarce resources in settings of uncertainty*.
>
> Cramton (1998: 746)

Spectrum floors impose restrictions on the *outcome* of the auction. The use of floors splits auction bidders into two categories: (a) those eligible to bid for the spectrum reserved through the floors; and (b) other bidders who are not eligible. It is convenient to refer to the first category of eligible bidders as the "opted-in" bidders – as explained below, as a safeguard to protect against bidders leveraging from reserved to unreserved spectrum Ofcom required the bidders wishing to compete for the reserved spectrum to opt in and confirm their willingness to pay for all relevant floors at the reserve prices. The floors mean that the outcome of the auction must include one opted-in bidder winning a floor (or a larger package including a floor). The reduction in bid value as a consequence of the floor constraint can be a measure of the sacrifice in auction efficiency to promote output efficiency.[18]

The application of spectrum floors means conceptually that there is an auction within an auction. Opted-in bidders compete against each other for the reserved spectrum since only one portfolio is ultimately reserved via the floor. Other bidders, plus opted-in bidders for spectrum amounts in excess of their floors, compete against each other for the remaining unreserved spectrum. An opted-in bidder that wishes to acquire not only one of her floors but also additional spectrum competes in the sub-auctions for both reserved and unreserved spectrum. Reserved spectrum represented 4-16% of the spectrum in the auction, so the large majority of available spectrum was unreserved.

There is also competition between the two sub-auctions, because the reserved spectrum is not a single portfolio of pre-specified frequencies, but one from a set of possible floors. The choice of floor to be reserved is determined by the bidding in both sub-auctions. The spectrum that is reserved through the auction is the floor which minimises any loss in bid value from reserving spectrum, reflecting the combination of the preferences of the winning opted-in bidder and the opportunity cost to non opted-in bidders.

Implementation challenges

The outcome restriction of spectrum floors is much less straightforward to implement than either simple spectrum reservation, i.e. set-aside of pre-specified frequencies, or spectrum caps. Both of these just represent restrictions on permissible bids. So bids that are not permitted can be identified and discarded or prevented, e.g. a bid that would take the bidder's holdings in excess of the spectrum cap.

[18] For an econometric analysis of the reduction in auction efficiency in the context of simple set-aside in the Canadian auction of Advanced Wireless Spectrum (AWS) in the 2GHz band, see Hyndman and Parmeter (2013).

Applying the outcome restrictions needed to implement floors was feasible in the auction format used by Ofcom, that of CCA.[19] Although the CCA design is complex, the intention is that it provides good incentives for bidders to bid truthfully, which would be highly desirable for auction efficiency.[20] The flexibility to add outcome restrictions in the form of spectrum floors also promotes output efficiency.

There is, however, potentially a trade-off between different aspects of output efficiency. On the one hand, an opted-in bidder acquiring spectrum in the 4G auction should strengthen downstream competition. But on the other hand, this might be offset if opted-in bidders have a lower private value of that spectrum than one or more of the three largest incumbents and if this auction inefficiency indicates lower social value in the output market.

A practical way to make this trade-off, given the difficulties in quantifying competition benefits, is to set a reserve price that is not too far below the expected willingness to pay of a reasonably efficient opted-in bidder using benchmark information from other auctions. If so, such reserve prices can promote output efficiency. If, as expected, there are opted-in bidders willing to pay the reserve prices, there is reasonable confidence that output efficiency will be promoted. Alternatively, if there is no candidate fourth national wholesaler willing to pay the reserve prices, the spectrum floors would not apply and no spectrum would be reserved. This might be appropriate as, with such lower values for the spectrum, a fourth national wholesaler might only have a limited impact on competition and so could fail to yield the desired competition benefits from spectrum floors. Ofcom set reserve prices (see Figure 2) using an approach along these lines, but also taking other considerations into account, such as making collusive bidding less profitable[21] (see Klemperer 2002).

There were a number of other implementation challenges, such as to mitigate the scope for gaming behaviour by opted-in bidders, who have a favoured status in the auction because they are the only bidders allowed to compete for the reserved spectrum. Without suitable safeguards this status could be exploited such as bypassing competition in the auction and leveraging from reserved to unreserved spectrum.[22] Such concerns were alleviated by the addition of an opt-in round with a requirement on eligible bidders wishing to compete for

[19] Ofcom was an early adopter of CCA for spectrum auctions, starting with the 10-40GHz auction in February 2008 followed by the L Band auction in May 2008. Ofcom also made a decision in April 2008 to hold a CCA for the 2.6GHz band, but this auction did not take place due to litigation and subsequent developments, and the 2.6GHz band was ultimately included in the 4G auction. The CCA has since been used for spectrum auctions in a range of other countries including Australia, Austria, Denmark, Ireland, Netherlands and Switzerland.

[20] See Cramton (2013). It is argued, however, in Janssen and Karamychev (2013) that CCAs significantly enhance the possibilities for strategic bidding. It is shown in Kagel et al. (2010) that auction efficiency depends on sufficiently aggressive bidding on efficiency-relevant packages and, using experimental analysis, that the risk of auction inefficiency depends on the circumstances given that bidders tend to bid on a small number of packages which are generally the most profitable, but do not include all profitable packages and may not always include the efficiency relevant packages.

[21] For details see Section 8 in Ofcom (2012b) and Section 3 in Ofcom (2012c).

[22] For example, assume there is a single opted-in bidder who only bids for a single package of 2x20MHz of 800MHz plus 2x55MHz of 2.6GHz at reserve prices, which is a superset of any of the floors in Figure 2 and is consistent with the sub-1GHz and total spectrum caps for H3G and new entrants. Since the outcome must include an opted-in bidder winning a floor and this is the only package bid by an opted-in bidder, this bid must win. The opted-in bidder therefore guarantees that it not only wins a floor of its choice but also any other, unreserved spectrum of its choice in the auction up to the level permitted by the caps.

reserved spectrum to opt in to all of their floors at reserve prices, so that the winning outcome could include any one of these bids, thereby restoring competition in the auction.

Another opportunity for gaming would be if an opted-in bidder could make bids that could never win. If so, it could, without risk, use such bids to try to affect the prices that others would pay for spectrum (given the second-price rule). An example is if there was only one opted-in bidder in the auction. In that case, to satisfy the spectrum floor constraint, the opted-in bidder would have to win a floor. Hence any bid by that single opted-in bidder for a package that did not contain a floor could not win. The scope for gaming in such circumstances was addressed by limiting the single opted-in bidder only to make bids on its floors or packages containing her floors, thereby preventing it from making the bids that could never win.

Therefore, implementing spectrum floors involved making sophisticated modifications to the design of the CCA, which is already complex. In doing so, the intention was to preserve desirable incentives for truthful bidding, since an objective in using spectrum floors is that the auction reveals the winning floor as the one that maximises the net benefit of reservation. However, whilst the scope for some types of strategic bidding by opted-in bidders was successfully removed by the design features outlined above, as discussed in Section D, H3G's bidding strategy for spectrum floors appeared to take advantage of its favoured status as the only opted-in bidder in guaranteeing that it would only pay the reserve price for its winning floor.

Expectations before the auction

In advance of the auction, the following might have been reasonable expectations about some key aspects relating to floors:

(a) Number of opted-in bidders. It would have been a surprise if no eligible bidder had been willing to pay the reserve price for each of its floors and so opt in, in particular H3G, the smallest incumbent. But since no new entrant expressed an interest in becoming a new national competitor, it would not have been unexpected if there had only been one opted-in bidder, given the scale of the reserve prices for the floors for new entrants of around £0.5 billion or more (see Figure 2).

(b) Winning spectrum floor. Since significant competition was expected for the scarce spectrum in the low frequency at 800MHz band, it seemed more likely that the winning floor would have been the higher frequency spectrum (ie for H3G, 2x20MHz of 2.6GHz rather than 2x5MHz of 800MHz).

(c) Price for winning spectrum floor. With little or no competition between opted-in bidders, the price for the winning spectrum floor might well have been at or close to the reserve price.

As we explain in Section D, the first and third of these pre-auction expectations were borne out by the actual bidding in the auction, but there was a surprise about the winning floor.

D. Bidding in the auction and winning spectrum floor

> *... even Three [H3G] executives were astonished that it [the 4G auction] resulted in their company acquiring the treasured low frequency spectrum at Ofcom's reserve price ...*
>
> *Financial Times* (14 March 2013)

We now consider the bids made in the 4G auction and the outcome with particular focus on the spectrum floors. After providing an overview of the bids, we explain the choice of the winning spectrum floor. This depended on both the preferences in the bids of the opted-in bidders and the opportunity costs as reflected in the bids by other bidders – we analyse each in more detail.

Overview of bidding

The spectrum in the 4G auction was in 4 lot categories:

A. 800MHz band:
   1. 4 lots of 2x5MHz; and
   2. 1 lot of 2x10MHz with an obligation to provide 98% indoor coverage;

C. Paired[23] 2.6GHz band: 14 lots of 2x5MHz;[24]

D. Concurrent low-power use of paired 2.6GHz;[25] and

E. Unpaired 2.6GHz band: 9 lots of 5MHz.

The CCA is a combinatorial (or package) auction, i.e. bidders make package bids for a combination of lots. For example, a bidder might place a bid for 2x A1 lots (2x 10MHz of 800MHz without coverage obligation) and 4xC lots (2x 20MHz of 2.6GHz). This package bid could either win or lose in its entirety. But it could not partially win as the constituent elements of the package could not be considered separately. Package bids eliminate exposure or aggregation risk, which can be important where there are complementarities or synergies between bands and for larger blocks within a band. For example, a bidder's value for 2.6GHz may depend on whether it will also win 800MHz. In the CCA the bidder can place a package bid which is a commitment to buy both at a defined price with no risk that it will win 2.6GHz but fail to win 800MHz or vice versa.

Auction prices for the winning packages are based on opportunity cost using a second-price rule, i.e. highest losing bids. The intention is to encourage truthful bidding and enhance auction efficiency as the auction price depends only on bids made by others, not the amount

[23] The most commonly used mobile technologies in the UK use paired spectrum, i.e. carriers for the uplink and downlink in different frequencies with Frequency-Division Duplexing (FDD). There are also technologies that operate in unpaired spectrum – the uplink and downlink are separated by time in the same frequency with Time-Division Duplexing (TDD). There are both FDD and TDD variants of the 4G technology, LTE. The 4G auction included both paired spectrum in lot categories A, C and D and unpaired spectrum in lot category E.

[24] Lot category B is omitted from this list, since it related to the 2x15MHz of 1800MHz to be divested by EE to meet commitments given at the time of the 2010 merger. If this spectrum had not been divested in advance, it would have been included in the auction, but in the event EE sold the spectrum to H3G before the auction.

[25] The auction design enabled bids from up to 10 low power users, who would share 2.6GHz spectrum i.e. concurrently use this frequency to provide local networks such as inside buildings. Such bids were aggregated to compete for 2x 10MHz (category D1) or 2x 20MHz (D2) of 2.6GHz against individual standard power users in category C. In the event the winning bids were only for C and did not include D1 or D2.

bid by the winning bidder.[26] An example of how second prices promote auction efficiency is that they remove the incentive for strategic demand reduction, because by bidding on a larger package a bidder does not increase the price it would have to pay if it won a smaller package. The derivation of opportunity cost prices for the winning spectrum floor is discussed in greater detail below.

There were seven bidders in the 4G auction: the four incumbent national wholesalers – EE, H3G, Telefónica and Vodafone; and three potential new entrants – HKT, MLL and Niche Spectrum Ventures (a wholly owned subsidiary of BT, the fixed line incumbent). The four incumbents made bids for all categories of spectrum; Niche bid for 2.6GHz, both paired and unpaired (but not for 800MHz); and HKT and MLL only made bids for unpaired 2.6GHz.

There were four stages of bidding in the 4G auction shown in Figure 3. The opt-in round was a feature specific to the use of spectrum floors in the UK auction. Of the remaining stages the most important in determining the outcome of the auction, including the choice of winning spectrum floor, was the supplementary bids round. For simplicity, in the discussion below we therefore abstract from bids in the clock stage and the assignment stage.[27]

Figure 3: Timetable of stages in 4G auction

Auction stage	Date in 2013	Comment
Opt-in round	18 January	Single opted-in bidder, H3G
Clock stage	23 January – 7 February	52 clock rounds
Supplementary bids round	12 February	277 bids by 7 bidders
Result of Principal stage	20 February	Winning packages and base prices
Assignment round	26 February	Assignment of specific frequencies
Licences issued	1 March	Completion of auction process

Opt-in round

The opt-in round took place on 18 January 2013. Only H3G and new entrants were eligible to bid for the spectrum reserved through floors and so to bid in the opt-in round for each relevant spectrum floor at reserve prices. Of these bidders, only H3G chose to make opt-in bids – in addition to the floors for H3G listed in Figure 2 above, it also took up the option to bid for the coverage obligation 800MHz spectrum (category A2):

(a) £225m for 2x5MHz of 800MHz (1 lot of category A1, ie 1xA1);
(b) £250m for 2x10MHz of 800MHz with coverage obligation (1xA2); and
(c) £60m for 2x20MHz of 2.6GHz (4xC).

[26] This is the case if prices are set at individual opportunity cost, so-called Vickrey prices although see Rothkopf (2007) for some reasons for departures from truthful bidding. The CCA is a core-selecting auction, meaning that, for each winning package and combination of winning packages, each bidder or coalition of bidders that failed to win that package did not place a higher bid than the price charged to the winner(s). The minimum revenue core is a unique set of prices if the set of individual opportunity costs for all winning bidders considered on their own is consistent with the collective opportunity costs for all combinations of winning bidders (i.e. if Vickrey prices are in the core). With the bids actually made in the 4G auction this was in fact the case. For the bidding incentive properties of core-selecting auctions, see Erdil and Klemperer (2010) and Milgrom (2011).

[27] Further details of the role of the clock stage and assignment round in a CCA are set out in Cramton (2013). Ofcom (2013b) sets out the bids by all bidders in all four stages of the 4G auction.

The new entrants chose not to compete for the reserved spectrum, which would have required them to make substantial bids including £675m for 2x15MHz of 800MHz, as shown in Figure 2.

Since there was only one opted-in bidder and this was announced to all bidders, it was known after the opt-in round that there would be no competition between bidders to obtain reserved spectrum, so H3G was guaranteed to win one of the three spectrum floors on which it made opt-in bids or a larger package including a floor. But there was still competition in the auction between H3G and other bidders over the choice of H3G's spectrum floor, 800MHz (category A1 or A2) or paired 2.6GHz (category C). However, as set out below, because H3G knew that it was the only opted-in bidder it was able to bid strategically, i.e. in a manner that may have departed from bidding its true intrinsic values. H3G's bidding strategy seemed designed to influence the price it would pay for its winning floor so that it would be no higher than the reserve price, but it could also have affected the choice of winning floor.

Supplementary bids round

The supplementary bids round took place on 12 February 2013. In total there were 277 bids, with a relatively small number of mutually exclusive package bids made by each of H3G (17), Telefónica (11), HKT (9) and MLL (9), but a larger number by EE (48), Niche (89) and Vodafone (94). These bids resulted in the outcome shown in Figure 4. As the only opted-in bidder H3G had to win one of its spectrum floors, or a larger package including a floor. Although it did bid for various larger packages, H3G's winning bid was for one of its floors, 2x5MHz of 800MHz.

Figure 4: Winning packages, bid amounts and prices in 4G auction

Winner	800MHz: A1	800MHz: A2	2.6GHz paired: C	2.6GHz unpaired: E	Reserve price	Bid amount	Base price
Lot size	2x5MHz	2x10MHz	2x5MHz	5MHz			
EE	2x5MHz (1xA1)		2x35MHz (7xC)		£330m	£1,049.5m	£588.876m
H3G	2x5MHz (1xA1)				£225m	£565.5m	£225m
Niche			2x15MHz (3xC)	20MHz (4xE)	£45.4m	£340.431m	£186.476m
Telefónica		2x10MHz (1xA2)			£250m	£1,219.003m	£550m
Vodafone	2x10MHz (2xA1)		2x20MHz (4xC)	25MHz (5xE)	£510.5m	£2,075.044m	£790.761m
Total	2x20MHz (4xA1)	2x10MHz (1xA2)	2x70MHz (14xC)	45MHz (9xE)	£1,360.9m	£5,249.478m	£2,341.113m
Total excl H3G	2x15MHz (3xA1)	2x10MHz (1xA2)	2x70MHz (14xC)	45MHz (9xE)	£1,360.9m	£4,683.978m	

Source: Author from Ofcom (2013a, b)

Choice of winning floor

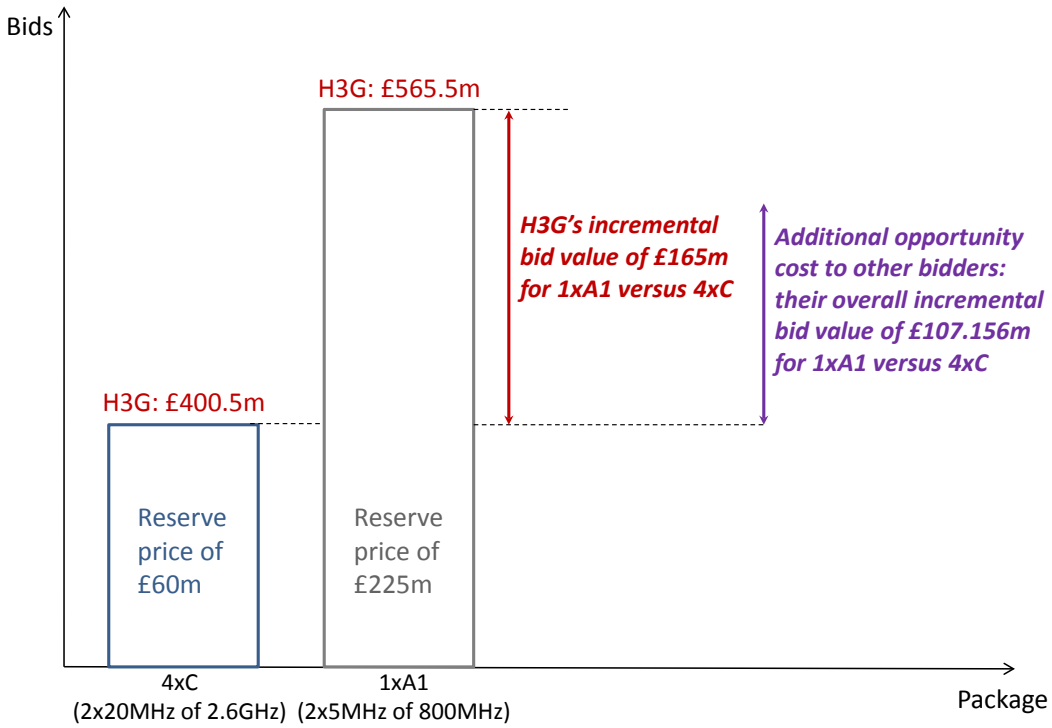
We now focus on the choice in the auction of the winning floor of 2x5MHz of 800MHz (1xA1) instead of 2x20MHz of 2.6GHz (4xC), which was determined by comparing the:

(a) incremental values in H3G's bids for its spectrum floors, as the beneficiary of the reserved spectrum; and

(b) opportunity cost for these spectrum floors to other bidders who were denied the ability to acquire the reserved spectrum.

Figure 5 summarises these two values in the 4G auction bids. H3G won the spectrum floor of 1xA1 instead of 4xC because the incremental value in its bids of £165m exceeded the additional opportunity cost to other bidders of £107.156m. (This was an "additional" opportunity cost because it was additional to other bidders' loss in bid value of £276.844m from H3G winning 4xC instead of them winning that as well as all of the other spectrum in the auction.) Below we consider in greater detail the bidding that led to this outcome, starting with H3G's bidding strategy and then assessing the elements of the opportunity cost to other bidders, especially the bids of EE.

Figure 5: Choice of H3G's winning floor



H3G's bidding strategy

H3G's supplementary bids are shown in Figure 6 – these include the bids that affected the auction outcome. One notable feature of H3G's bids for its three spectrum floors is that it chose incremental bid values that reflected the differences in reserve prices. In particular, H3G's bid for 1xA1 (package 7) was £165m higher than its bid for 4xC (package 1) – the reserve price for 1xA1 of £225m was £165m higher than for 4xC of £60m. This incremental

bid value of £165m for 1xA1 versus 4xC also applied to the differences in H3G's bid amounts between various pairs of its larger packages where the difference in spectrum between the packages was substituting 1xA1 for 4xC, i.e. packages 8 versus 2, 9 versus 3, and 10 versus 4.[28]

It is possible that the relativities in Ofcom's reserve prices precisely captured H3G's true incremental values for the spectrum floors, although that would be a considerable coincidence. Perhaps the more likely explanation is that it was a bidding strategy by H3G which guaranteed that it would not pay more than the reserve price for its winning spectrum floor.

To see why H3G's bids might reflect such a strategy, we need to understand how the price of its winning floor was determined based on opportunity cost under the second-price rule used in the auction. As the only opted-in bidder, H3G would have known that the price it would pay for its winning floor would reflect the reserve price of the other floor and the additional opportunity cost to other bidders.[29] Specifically, using the actual additional opportunity cost of £107.156m to illustrate:

(a) If H3G's incremental bid value for 1xA1 were above other bidders' additional opportunity cost (as was the case in practice), its winning floor would be 1xA1 at a price determined as the higher of:
   (i) reserve price of the other floor, 4xC, which other bidders preferred it to win, plus the additional opportunity cost imposed on those other bidders, i.e. £60m + £107.156m = £167.156m; and
   (ii) reserve price of the winning floor, 1xA1, of £225m (this was the binding constraint in practice with the additional opportunity cost of £107.156m).

(b) On the other hand, if H3G's incremental bid value were below other bidders' additional opportunity cost, its winning floor would have been 4xC at a price determined as the higher of:
   (i) reserve price of the other floor, 1xA1, less the additional opportunity cost to other bidders that would be avoided, i.e. £225m - £107.156m = £117.844m; and
   (ii) reserve price of the winning floor in this scenario, 4xC, of £60m.[30]

[28] H3G's bid for its third floor of 1xA2 (package 12) was £25m higher than its bid for 1xA1 (package 7) – the reserve price for A2 was £250m, compared to £225m for A1.

[29] Together these elements would give the Vickrey price and were independent of H3G's own bids. In addition there was the possibility that the Vickrey price would lie outside the core, in which case the price would also include a core adjustment which would not necessarily be independent of H3G's own bids.

[30] This description is a simplification. Firstly, since a bidder can never be asked to pay a price higher than the amount it bid for that package, the level of H3G's bids could also have been a constraint on prices although this was not the case in practice, as the level of H3G's bids for its floors were substantially above the level of reserve prices. Secondly, there can be core adjustments that increase the price if Vickrey prices lie outside the core e.g. this could have been the case if H3G had bid an incremental value below £107.156m and won the floor of 4xC.

Figure 6: H3G's supplementary bids

	A1	A2	C	D2	E	Bid amount	Comment
1			**2x20MHz**			**£400.5m**	**Floor of 4xC**
2			2x20MHz		20MHz	£422.5m	
3			2x20MHz		25MHz	£430.5m	
4			2x20MHz		45MHz	£460.5m	
5			2x25MHz			£440.5m	
6			2x30MHz			£500.5m	
7	**2x5MHz**					**£565.5m**	**Winning bid, floor of 1xA1**
8	2x5MHz				20MHz	£587.5m	
9	2x5MHz				25MHz	£595.5m	
10	2x5MHz				45MHz	£625.5m	
11	2x5MHz		2x10MHz			£665.5m	
12		**2x10MHz**				**£590.5m**	**Floor of 1xA2**
13		2x10MHz	2x10MHz			£690.5m	
14		2x10MHz	2x50MHz	2x20MHz	35MHz	£1,299.965m	
15	2x10MHz		2x50MHz	2x20MHz	35MHz	£1,464.424m	
16	2x5MHz	2x10MHz	2x50MHz	2x20MHz	25MHz	£1,601.090m	
17	2x15MHz		2x50MHz	2x20MHz	25MHz	£1,693.095m	

Source: Author from Ofcom (2013b)

H3G was able to ensure it would never pay more than the reserve price for its winning floor, regardless of the additional opportunity cost (which, of course, H3G did not know when it was making its bids), by bidding an incremental value equal to the difference in reserve prices of £165m. This is because:

(a) Either the additional opportunity cost would be less than H3G's incremental value of £165m, in which case the winning floor would be 1xA1. Since the additional opportunity cost would be less than £165m, the price for 1xA1 would be the reserve price of £225m because the sum of the reserve price of 4xC of £60m and the additional opportunity cost would have to be less than the reserve price of 1xA1 of £225m.

(b) Or, in the alternative, the additional opportunity cost would be larger than H3G's incremental value of £165m, in which case the winning floor would be 4xC. Since the additional opportunity cost would be greater than £165m, the price for 4xC would be the reserve price of £60m because the reserve price of 1xA1 of £225m less the additional opportunity cost would have to be less than the reserve price of 4xC of £60m.

To the extent that its true incremental values for its different spectrum floors varied from the differences in reserve prices, H3G seemed to be favouring only paying the reserve price over winning its preferred spectrum floor. As such, it seems likely that H3G made strategic bids in the sense that term is defined in this paper, i.e. its bids departed from its true intrinsic values. Since we do not have information on H3G's true values, we do not know whether such a departure was relatively small or very significant. If H3G's true incremental intrinsic value for its floors were very different from the difference in reserve prices of £165m, it would have faced a conflict between:

(a) improving its chances of winning its preferred floor at the risk of paying somewhat above the reserve price; and
(b) only paying the reserve price but at the risk of winning its less preferred floor.

Either H3G faced this conflict and favoured paying no more than the reserve price, or the conflict was not large because its true incremental value did not depart substantially from £165m.

If H3G had faced competition from other opted-in bidders, it would have been at risk in departing from its true incremental values.[31] The bidding strategy H3G adopted could have reduced its chances of winning reserved spectrum or led to it paying in excess of its true value for the winning floor. However, H3G knew with certainty after the opt-in round that it was the only opted-in bidder, which allowed it to adopt its chosen bidding strategy without facing those risks.

H3G's bidding strategy provides an example of the opted-in bidder taking advantage of its favoured status in the auction as the only bidder allowed to bid for reserved spectrum. The scope for some types of strategic bidding by opted-in bidders was successfully removed (see Section C), but not all.

H3G won the spectrum floor of 1xA1, because of the incremental value in its supplementary bids of £165m for 1xA1 versus 4xC. Although this incremental bid value was the same as the difference in reserve prices, it comfortably exceeded the incremental value of other bidders, as discussed in greater detail below.

Opportunity cost to other bidders

The additional opportunity cost to other bidders for H3G to win its spectrum floor of 1xA1 instead of 4xC was £107.156m, as shown in Figure 5. This additional opportunity cost constituted other bidders' overall incremental value for 1xA1 instead of 4xC – that is, the difference in their highest value bid combinations as between their bids for the:

(a) counterfactual with H3G winning the floor of 4xC: other bidders' highest total bid value for all the spectrum in the auction including H3G's spectrum floor of 1xA1 but excluding its other floor of 4xC, consistent with H3G winning that floor (£4,791.134m); and
(b) actual winning combination with H3G winning the floor of 1xA1: other bidders' highest total bid value for all the spectrum in the auction including H3G's losing spectrum floor of 4xC but excluding the floor of 1xA1 which was won by H3G (£4,683.978m – see the last row of Figure 4).

The breakdown of bids by EE is of particular interest in this context as it was the only bidder (other than H3G) that expressed a direct incremental value for 1xA1 versus 4xC.[32] EE's bids contributed to H3G's winning spectrum floor being 1xA1 instead of 4xC.

[31] Or true absolute values in the level of its bids – see the discussion in the sub-section below on Intrinsic values.
[32] HKT, MLL and Niche did not make any bids for 800MHz; and all of Telefónica's and Vodafone's bids for 800MHz included 2x10MHz – neither made any bids for 2x 5MHz (1xA1) and the sub-1GHz cap prevented them from bidding for 2x15MHz.

As actually occurred, EE might reasonably have expected that its bids would have a significant influence on the spectrum floor won by H3G. This is because each of Telefónica and Vodafone bid strongly for 2x10MHz of 800MHz (2xA1 or 1xA2), and neither was permitted to bid for any larger quantity because of the sub-1GHz cap. Given this, H3G would only acquire a floor of 800MHz spectrum if EE won less than 2x10MHz in that band; and if not, H3G would need to win the floor of 4xC. EE chose to bid aggressively for large quantities of category C (paired 2.6GHz) up to 7xC, i.e. one-half of the entire band and, of particular interest in this context of the choice of H3G's winning spectrum floor, as between 1xA1 and 4xC it generally bid more aggressively at the margin for 4xC than for an additional 1xA1. We can compare, in particular, EE's bids for the following two packages:

(a) 1xA1 plus 7xC (2x 5MHz of 800MHz plus 2x35MHz of 2.6GHz), consistent with H3G winning the spectrum floor of 1xA1; and
(b) 2xA1 plus 3xC (2x10MHz of 800MHz plus 2x15MHz of 2.6GHz), consistent with H3G winning the spectrum floor of 4xC.

EE made a lower bid of £1,035.478m for the second package compared to its (winning) bid for the first package of £1,049.5m – this was therefore a *negative* incremental value (or negative component of additional opportunity cost) of -£14.022m. Such bidding by EE suggests that it preferred H3G to win the spectrum floor of 1xA1 than the floor of 4xC. EE's negative component of additional opportunity cost compared to the positive incremental value of £165m in H3G's bids.[33]

The composition of the additional opportunity cost of £107.156m can therefore be presented as:

(a) negative component of additional opportunity cost of -£14.022m which is EE's negative incremental value for 1xA1 versus 4xC (as set out above, EE's difference in bid amount for 2xA1 plus 3x C compared to 1xA1 plus 7xC); and
(b) positive component of additional opportunity cost of £121.178m.[34]

This emphasises that the additional opportunity cost to other bidders was reduced by EE's negative incremental value for 1xA1 compared to 4xC. Such bidding by EE increased the chances of H3G winning its spectrum floor of 1xA1, not 4xC.

[33] EE also bid a negative incremental value of -£34m for the package of 2xA1 plus 2xC compared to the package of 1xA1 plus 6xC (£865m versus £899m), again suggesting a preference for H3G to win 1xA1 than 4xC. However, for one further relevant comparison, EE expressed an incremental value in the opposite direction as it made a higher bid for 2xA1 compared to 1xA1 plus 4xC, by £10.001m (£650.001m versus £640m). But this incremental value was small and, in particular, much smaller than the incremental value in H3G's bids. There are no further relevant direct comparisons in EE's bids. EE did not make a bid for 2xA1 plus 1xC; and it was not permitted to bid for a larger package than 1xA1 plus 7xC because of the cap on total spectrum holdings.

[34] In a package auction a change of a set of bidders winning one lot (1xA1) rather than another set of lots (4xC) can imply a full re-arrangement of all of the packages won by those bidders, not just a change at the margin for one bidder. This was the case for the comparison of the two combinations which represent other bidders' additional opportunity cost – the counterfactual also involved a rearrangement of 3xC from EE to Telefónica and Vodafone, and 9xE from Vodafone and Niche to EE, i.e. EE's package in the counterfactual was 2xA1 plus 9xE; Niche's was 3xC; Telefónica's was 1xA2 plus 2xC; and Vodafone's was 2xA1 plus 5xC.

Auction efficiency

H3G was reported in *Financial Times* (2013) as being "astonished that it [the auction] resulted in their company acquiring the treasured low frequency spectrum at Ofcom's reserve price". But H3G acquiring a spectrum floor at the reserve price cannot have been a surprise to H3G as its bidding strategy guaranteed this would be the case, as set out above. As regards acquiring the spectrum floor of 2x5MHz of 800MHz (1xA1) instead of the floor of 2x20MHz of 2.6GHz (4xC), whilst H3G's incremental value of £165m did not guarantee that H3G would win the floor of 2x5MHz of 800MHz, as set out above, it was the winning spectrum floor because it turned out to be in excess of the additional opportunity cost in bids by other bidders in aggregate of £107.156m. H3G's surprise might have been that it expected this additional opportunity cost to be higher.

For auction efficiency, the winning spectrum floor should be the one which, using true values, has the largest incremental value to the beneficiary, H3G, net of the additional opportunity cost to other bidders. We do not know bidders' true values, so we do not know how closely their bids correspond to them, or how far they deviate, as noted above in the context of H3G's bidding strategy. This limits the ability to make an assessment of auction efficiency. Whilst H3G's bidding strategy ensured it would pay no more than the reserve price for its winning floor, it did not guarantee which of the spectrum floors it would win. The additional opportunity cost to other bidders was lowered by the negative incremental value in EE's bids (of -£14.022m), which was not an isolated feature and applied to other incremental values in EE's bids. Assuming that the additional opportunity cost of other bidders reflected truthful bidding, the choice of winning floor was distorted from the efficient outcome by H3G's bidding strategy only if H3G's true incremental value for 1x A1 over 4x C was less than £107.156m, i.e. almost £58m less than its actual incremental bid amount of £165m.

Ofcom's competition assessment and evidence from bids made

As discussed in Section B, Ofcom's rationale for spectrum floors was to further output efficiency by promoting competition among at least four national wholesalers, given the risk of market failure that H3G or a new entrant would fail to acquire the spectrum it required to be an effective constraint on its rivals without spectrum reservation. The two potential sources of market failure Ofcom identified were asymmetries in intrinsic value and strategic investment by the three large incumbents (EE, Telefónica and Vodafone).

Intrinsic values

Superficially it appears that the bidding in the auction does not provide evidence to support the first market failure of H3G having lower intrinsic value than the larger incumbents for the spectrum it required (i.e. its floors). This is because H3G's bid for 1xA1, its winning spectrum floor, was sufficiently high at £565.5m that it would have won this same spectrum even in the absence of spectrum floors, assuming that the same bids had been made by others.[35] This seems to imply that there was no sacrifice in auction efficiency in the use of floors to promote output efficiency.

[35] The only difference would have been that H3G would have paid a higher price for 1x A1 of £384m (£159m higher than the price it paid with spectrum floors of £225m).

But, especially given the analysis of H3G's bidding strategy set out above, taking H3G's bids at face value would not provide a robust conclusion on relative intrinsic values. This is because the operation of spectrum floors meant that the *level* of H3G's bids did not matter, only the relativities or incremental values between its bids for its spectrum floors, and H3G would have known this. Our analysis above suggested that, by bidding incremental values equal to the differences in reserve prices, H3G guaranteed that it would win a spectrum floor at the reserve price regardless of the bids made by others. It could have established such incremental values with bids at any level (at or above reserve prices) and achieved the same result. In other words, due to the existence of spectrum floors and with H3G being the only opted-in bidder, when it made a bid of £565.5m for 1xA1, it knew that it would only have to pay £225m if that was its winning bid, given the other bids it made for its floors and regardless of the bids made by others. This makes it questionable to rely on the level of its winning bid of £565.5m as a true reflection of its intrinsic value for 2x5MHz of 800MHz, as in the circumstances it could be an overstatement (or an understatement). Hence bids in the auction do not provide reliable evidence to test Ofcom's concern about market failure relating to intrinsic value.

Strategic investment

The second market failure of strategic investment by the three large incumbents is even harder to evaluate using the bid data. This is because one of the purposes of the imposition of spectrum floors was to undermine the incentive to engage in such behaviour, given that the floors ensured that H3G or a new entrant would acquire a minimum portfolio of spectrum in the auction. Therefore, the bids actually made in the presence of spectrum floors do not provide a reliable guide to the bids that would have been made in their absence.

Minimum amount of 800MHz required

One of Ofcom's conclusions was that 2x5MHz of 800MHz spectrum was sufficient for H3G to be capable of providing an effective constraint on its rivals (given that it already held 2x15MHz of 1800MHz spectrum). If 2x5MHz had been insufficient, we might have expected H3G to make bids at relatively high incremental values for 2x10MHz of 800MHz. But in fact H3G made only four such bids (packages 12, 13, 14 and 15 in Figure 6), two of which were part of such large packages that they did not play a role in influencing the outcome of the auction (as H3G could have anticipated) and the other two were at a low, not high incremental value of only £25m (package 12 at £590.5m versus package 7 at £565.5m, and package 13 at £690.5m versus package 11 at £665.5m).[36]

EE's bids suggest that there was a significant synergy value in 2x10MHz compared to 2x5MHz of 800MHz. The incremental values in its bids for the first 2x5MHz of 800MHz (1xA1) were typically £230m, although there were also a few higher incremental values including £353m in its winning bid.[37] Its incremental values for the second 2x5MHz to create a 2x10MHz block of 800MHz were significantly higher at between £420m and £610m.

[36] Packages 12 and 13 in Figure 6 included 2x10MHz of 800MHz with the coverage obligation (category A2) and so these incremental values may have been depressed by the cost of the coverage obligation to H3G. However, it was H3G's choice not to make more and/or higher bids for packages including 2x10MHz in category A1 which would have avoided that cost.

[37] £1,049.5m for 1xA1 plus 7xC compared to its bid of £696.5m for 7xC.

But if 2x10MHz of 800MHz were essential and 2x5MHz of little value, we might have expected EE's bids to display even larger synergies or for it only to bid for packages with 2x10MHz of 800MHz. In fact it made 11 bids for packages including 2x5MHz of 800MHz, 23% of all of its supplementary bids, and these included its winning bid.

Ofcom also reached the conclusion (contentious at the time) that sub-1GHz spectrum was not essential for a national wholesaler to provide an effective competitive constraint if it held at least 2x15MHz of 1800MHz. In addition to H3G's bid on the spectrum floor of 2x20MHz of 2.6GHz, a package on which it was required to bid if it wanted to obtain the reserved spectrum, H3G chose to make 5 supplementary bids for packages without 800MHz, a significant proportion of its total of 17 bids. EE made bids for 12 packages that included no 800MHz, which, if any had won, would have left it without any sub-1GHz spectrum.

E. Conclusions

Flexibility is better than predictability.
Evinda Lepins

Through the UK 4G auction Ofcom pursued an objective to promote mobile competition between at least four credible national competitors. An evaluation of the success of this approach in terms of output efficiency is beyond the scope of this paper and in any case it is too soon to assess either the effectiveness in promoting mobile competition or the impact on consumers. The focus of this paper has instead been the choice of competition measure in the auction to achieve that objective, i.e. the use of the new regulatory tool of spectrum floors, the flexible reservation of a portfolio of spectrum for either a new entrant or the smallest incumbent national mobile competitor (H3G).

The innovation in spectrum floors is their two dimensions of flexibility: different portfolios of spectrum can be reserved for different players, e.g. depending on their pre-auction spectrum holdings; and the choice of spectrum to be reserved from a range of portfolios, each of which is sufficient to promote competition, is decided through the auction as the floor that minimises the loss in bid value from reservation.

The use of spectrum floors emphasised output efficiency through promoting downstream competition. Its implementation in the auction sought also to maximise auction efficiency (subject to the constraint of the floor, i.e. maximise the benefit of reservation net of opportunity costs) through sophisticated modifications to the already complex design of the CCA. This approach represented a balance between the risks of market and regulatory failure. On the one hand, H3G or a new entrant might fail in the auction to acquire the spectrum required for promotion of downstream competition because of asymmetries in intrinsic value compared to social value or strategic investment by the larger incumbents (EE, Telefónica and Vodafone) to foreclose spectrum to competitors. On the other hand, using the traditional approach of spectrum set-aside, the regulator might fail to choose the most efficient spectrum to be reserved, because of misjudging the spectrum preferences of operators benefiting from the reserved spectrum relative to the opportunity cost to other operators of reservation. With

spectrum floors the choice of spectrum to be reserved is based on the market information in auction bids, not the regulator's judgement.

In the 4G auction held in January to February 2013 the full potential of spectrum floors was not, in the event, tested because there was no competition between bidders eligible to obtain reserved spectrum – H3G was the only such bidder willing to pay the reserve price of the spectrum floors. However, there was still competition over the choice of spectrum floor for H3G, which resulted in a surprising outcome. H3G won the spectrum floor of 2x5MHz in the higher-value 800MHz band, i.e. scarce sub-1GHz spectrum, rather than a larger amount of spectrum in the lower-value band, 2x20MHz of 2.6GHz. An analysis of the bids as between these two floors shows that the incremental value for the 800MHz floor in H3G's package bids (of £165m) exceeded the additional opportunity cost to other bidders (of £107.156m). This market information on the value to the beneficiary was affected by H3G's strategy of bidding incremental values for the floors equal to the differences in their reserve prices, which guaranteed that it would not pay more than the reserve price for its winning floor but may have departed from its true values. The additional opportunity cost of the winning floor to other bidders was reduced by EE's generally more aggressive bidding at the margin for 2x20MHz of 2.6GHz compared to 2x5MHz of 800MHz.

Even if the market information in the auction used to choose the winning spectrum floor to be reserved may have been imperfect because of H3G's strategic bidding, the efficient choice of floor was made unless the departure from true values in H3G's (and/or other bidders') incremental value was significant, given the margin by which H3G's incremental bid value exceeded the additional opportunity cost to other bidders. Furthermore, in judging the overall success of spectrum floors in the UK auction, the relevant question is whether the risk of auction inefficiency from imperfect market information was preferable to the risks associated with a decision by the regulator on the specific frequencies to reserve (as under simple set-aside, an alternative to spectrum floors) which would also have been based on imperfect information with a significant risk of regulatory failure.

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