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Rationalizing the 3.4-3.8 GHz Spectrum in the United Kingdom

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1 Introduction

The 3.4-3.8 GHz frequencies represent the first mid-band spectrum available for the deployment of 5G services in the UK. Unlike 3G and 4G spectrum previously let at UK auctions, the 3.4-3.8 GHz range contains legacy allocations that create toehold positions and limit access to frequencies that have not yet been allocated. These legacy allocations limit operators' ability to obtain enough contiguous bandwidth for 5G services, and, if left unaddressed, threaten to lower the social value of the entire band.

In advance of auctioning the remaining unallocated spectrum in 3.6-3.8 GHz, Ofcom has the opportunity to adopt a band-restructuring framework that gives wireless providers the option of acquiring the necessary spectrum to use this first 5G band to its full potential. The core element of the framework would be to guarantee that post-auction holdings are assigned to contiguous frequencies within the entire 3.4-3.8 GHz band for every licence holder regardless of when and how that spectrum was allocated.[2]

In this paper, we propose a detailed framework for rationalizing holdings in the 3.4-3.8 GHz band. The main component of the framework is an auction mechanism to determine post-auction frequency assignments by minimizing relocation costs. We discuss variations of this basic idea as well as alternatives. This framework is related to the band-restructuring frameworks that have become more common as regulators seek to reconfigure, reallocate, and repurpose spectrum holdings in response to changes in demand and technology. Examples of band-restructuring frameworks include the US Federal Communications Commission's (FCC) Broadcast Incentive Auction and its voucher-based proposal to reconfigure the 39 GHz band through an auction.[3] Mexico's use of credits to rationalize holdings in its 2015 AWS auction is another example.

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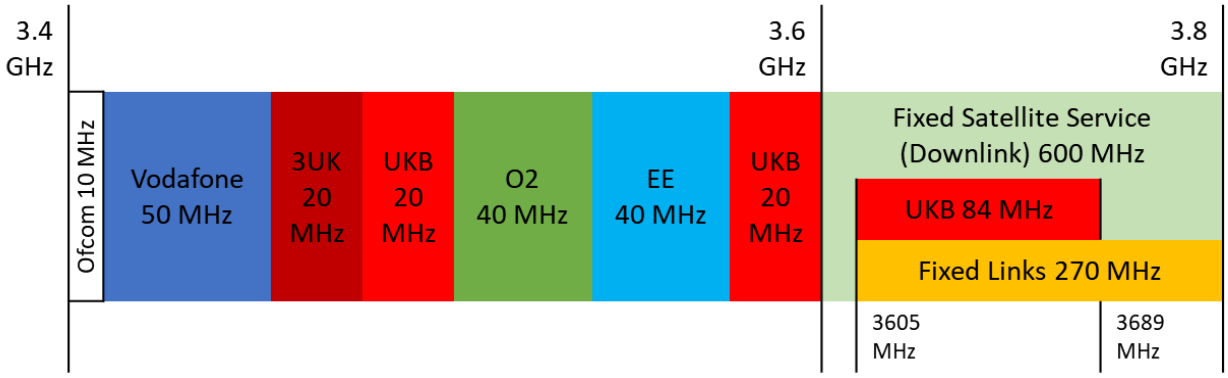
[2] The framework proposed here works with any degree of contiguity. For instance, if 3UK demands only 100 MHz of their holdings to be contiguous, as was contemplated in *Variation in of UK Broadband's Spectrum Access License for 3.6 GHz Spectrum: Ofcom's consideration of a request to vary the permitted lower frequency block*, published 27 June 2018, available at: https://www.ofcom.org.uk/__data/assets/pdf_file/0017/115343/Variation-UK-Broadband-Licence-3.6-GHz-spectrum.pdf, then this is a straightforward matter of relaxing one of the constraints in our assignment mechanism.

[3] See The FCC's Broadcast Incentive Auction Website at https://www.fcc.gov/about-fcc/fcc-initiatives/incentive-auctions. For background on the 37/39 GHz proposal, see *Use of Spectrum Bands Above 24 GHz for Mobile Radio Services*, GN Docket No. 14-177, Fourth Further Notice of Proposed Rulemaking, FCC 18-73 (August 3, 2018). This proposal is based on prior work by Bono, J. and Ingraham, A., "An Auction Design for Millimeter Wave Spectrum," Attachment to Letter from Alex Starr, Assistant Vice President, AT&T, to Marlene H. Dortch, Secretary, FCC, GN Docket No. 14-177 et al., at 2, Attach. at 3-5 (filed Dec. 12, 2017) (AT&T Dec. 12, 2017 Ex Parte). For an earlier description of a similar mechanism, see also, FCC, OPP Working Paper Series #38, November 2002. Kwerel and Williams, "A Proposal for a Rapid Transition to Market Allocation of Spectrum." https://apps.fcc.gov/edocs_public/attachmatch/DOC-228552A1.pdf

Individuals educated in the history of the 3.4 to 3.8 GHz spectrum in the UK are aware of the challenges that face operators in that band. Figure 1 (not drawn to scale) provides an illustration of current holdings.

Figure 1: Current holdings in the 3.4-3.8 GHz band.[4]



The obvious challenge facing both operators in this band and Ofcom, which seeks to allocate and assign the remaining spectrum in the 3.6-3.8 GHz range, is that contiguous bandwidth (and ideally contiguous swaths of 80 to 100 MHz of it) is presently suggested as the ideal for mid-band 5G.[5] Indeed, in emphasizing the importance of making large contiguous swaths available, GSMA recommends band restructuring like the framework we outline in this paper, "If countries are assigning spectrum in one range in multiple phases in order to gradually migrate incumbents (e.g. assigning 3.4-3.6 GHz then 3.6-3.8 GHz), the process should involve re-planning the band afterwards to allow operators to create larger contiguous blocks."[6] With respect to economic efficiency, we assume that the 5G product that UK consumers experience would improve in both price and quality were multiple wireless providers able to amass sufficient contiguous mid-band spectrum for delivering optimal 5G speeds.

2 Addressing Toehold Positions in the 3.4-3.8 GHz Band

If Ofcom does not have sufficient authority to force rationalization upon incumbent spectrum holders,[7] it then needs to present it as an option, with a carrot, within the context of an auction design. 3UK has

[4] Figure adapted from Ofcom, *Consultation: Variation of UK Broadband's spectrum access licence for 3.6 GHz spectrum*, June 27, 2018, at 7, available at: https://www.ofcom.org.uk/consultations-and-statements/category-2/variation-uk-broadbands-spectrum-access-licence-3.6-ghz.

[5] "5G Spectrum: GSMA Public Policy Position," p. 2, November 2018, available at: https://www.gsma.com/spectrum/wp-content/uploads/2018/11/5G-Spectrum-Positions.pdf.

[6] See https://www.gsma.com/spectrum/wp-content/uploads/2018/11/5G-Spectrum-Positions.pdf, at 4.

[7] By contrast, in its 4th Report and Order on the Use of Spectrum Bands above 24 GHz for Mobile Radio Services, the FCC noted that it had such authority and that during its consultation process on rationalization of spectrum in the 38 to 40 GHz band no respondent challenged this authority (the FCC Report and Order is available at: https://docs.fcc.gov/public/attachments/DOC-355211A1.pdf, and the FCC discusses its legislative authority at paragraph 9).

already stated its objective to obtain 100 MHz of contiguous spectrum in the band, and should therefore accept rationalization.[8] Vodafone, O2, and BT would presumably all agree to rationalize existing bandwidth with additional spectrum acquired in the 3.6 to 3.8 GHz auction should that auction occur in the near term. A complication, however, is that the short-term costs of rationalization may outweigh the benefits if the auction does not occur within a reasonable timeframe. Specifically, as operators begin to deploy their existing spectrum in the 3.4 to 3.6 GHz band, the costs of retuning or reconfiguring their networks may begin to outweigh the benefits of rationalization. Therefore, for the best chance at rationalizing the band, Ofcom should act soon to clarify the future of the band and its plans for moving incumbents to contiguous holdings.

With this caveat in place, we provide several auction-based innovations that would allow for the rationalization of the 3.4 to 3.8 GHz band were 3UK, Vodafone, O2, and BT/EE to agree to rationalization.

3 Auction Design

Here we propose an innovation to the assignment stage of the auction. This innovation would facilitate the sale of unallocated spectrum in the 3.4-3.8 GHz range and simultaneously reorganize and reassign legacy allocations, thus rationalizing the band. However, because the assignment stage is conducted after an initial allocation stage, we also briefly discuss the allocation stage. Importantly, the assignment innovation is independent of the intricacies of the allocation mechanism. For example, Ofcom has consulted on coverage obligations for spectrum in the auction of 700 MHz and may yet refine its proposals further. So long as that obligation does not apply to specific blocks or assignments in the 3.6-3.8 GHz range, it would not affect the framework discussed here.

3.1 Allocation Stage

The allocation stage should allocate frequency-generic spectrum and determine base prices for that spectrum. The three most popular auction mechanisms used worldwide are the generic SMRA, the uniform-price clock auction, and the CCA.[9] Ofcom could use any of these designs to conduct an allocation of generic spectrum and to determine base prices for that frequency-generic spectrum. Although the assignment mechanism discussed here is relevant to 3.6-3.8 GHz only, the allocation phase could also include 700 MHz spectrum and potentially other spectrum as Ofcom deems desirable. The

[8] See Ofcom, *Consultation: Variation of UK Broadband's spectrum access licence for 3.6 GHz spectrum*, June 2018, available at: https://www.ofcom.org.uk/consultations-and-statements/category-2/variation-uk-broadbands-spectrum-access-licence-3.6-ghz.

[9] Generic simultaneous multi-round auctions (SMRAs) have been used to allocate LTE spectrum in Spain (2010) and LTE and 5G spectrum in the UK (2018). Uniform-price clock auctions have been used in the United States, Mexico, Singapore, Saudi Arabia, and Taiwan to allocate spectrum. Other than the CCA, the uniform-price clock auction has proven to be the most common form frequency-generic spectrum auction worldwide since 2008. The combinatorial clock auction (CCA) was the most common form of mechanism to allocate LTE spectrum in Europe. It has also been used in one auction in Mexico (2015) and is presently the auction mechanism of choice in Canada.

main restriction on the allocation stage is that the mechanism should allocate generic spectrum lots rather than specific frequencies.

In addition, the auction supply for the 3.6 GHz category should ideally be the 120 MHz of unallocated spectrum in the 3.6-3.8 GHz range.[10] Separate product categories would exist for additional bands included in the auction (for example, 700 MHz). The usual rules would apply, including an activity rule based on eligibility points that would be fungible across product categories.

3.2 Assignment Stage Basics

The most important component of a plan to rationalize holdings in 3.4-3.8 GHz is the inclusion of a properly formulated assignment stage. In rationalizing the band, there are two competing concerns. The first is that spectrum holders are able to consolidate their spectrum into contiguous swaths that maximize technical efficiency. The second is that such a consolidation necessarily means that at least some incumbents will need to relocate their current frequency assignments. While relocating frequency assignments comes with costs, it is generally understood that they are outweighed by the efficiency gains from consolidation over the long term. Were that untrue, there would be no case for rationalizing the bandplan.

Before introducing the assignment stage framework, we note that it assumes that all incumbents participate in the rationalization process. Without that assumption, there must be contingencies for each possible set of holdouts, which would also depend on specific post-auction holdings. Only Vodafone, with its current position at the bottom of the band, could hold out of the rationalization process without severely undermining the contiguity prospects of the remaining incumbents. In contrast, with 3UK's position scattered throughout the band, it must participate for rationalization to occur.

3.3 A Relocation Cost-Based Assignment Stage

The innovation we propose involves the use of relocation cost modelling as a basis for frequency assignments. Prior assignment stages have entirely relied upon the expression of bidder value. That is, winning participants in the allocation phase of the auction are normally allowed to express their values for certain frequency assignments, with the winning assignments determined by searching for the feasible assignments that yield the highest sum of bids. Here, we focus on mechanisms for determining frequency assignments through the minimization of total relocation costs for incumbents in the band.

One benefit of the assignment stage mechanism proposed here is that it confines competition to the allocation stage, which gives bidders certainty that they do not need to hedge their allocation stage bidding against the possibility of worst-case relocation costs, split assignments, and/or excessive assignment pricing. That is, the framework takes away distortionary effects that uncertainty about the

[10] Here we include 3UK's 4 MHz fractional position with the auction supply and suggest that 3UK could receive a credit for that fractional position at auction clearing prices were such a credit allowable under Ofcom's authority.

assignment stage can have on allocation stage bidding. This adjustment should create a more efficient allocation stage and total auction outcome.[11] Another benefit is that it does not require incumbents to pay for assignments. This is particularly appealing in the 3.4-3.8 GHz band, where incumbents have already paid for assignments and are more concerned with achieving contiguity with minimal relocation costs.

Because the relocation cost model plays such a pivotal role in the assignment mechanism, it is worthwhile to describe it in more detail. The key feature of the relocation cost model is that it must calculate incremental relocation costs only, i.e. those costs that can only be attributed to the relocation of current frequency assignments and cannot be attributed to any other source. For example, any costs incurred as a result of acquiring additional spectrum at auction should not be included in the relocation cost model. Software and hardware upgrades, antennae tuning, and site visits required to bring new spectrum online would not be considered relocation costs, *even if those costs simultaneously addressed the relocation of existing holdings*. Ideally, Ofcom and the incumbents would agree on a relocation cost model for this framework through a normal consultation and/or negotiation process.

Although a comprehensive relocation cost model is the most appropriate objective to use in this framework, an alternative objective that merely approximates relocation costs can be used if needed.[12] For example, instead of minimizing relocation costs, the framework could instead maximize the MHz overlap of current and rationalized assignments. This alternative makes sense if relocation costs depend on the total quantity of MHz relocated. Or, if relocation costs are more binary in nature, such that an incumbent incurs some fixed level of relocation costs whenever it moves and has zero cost when it

[11] To see this, consider the difference in preferences expressed in assignment versus allocation in the 3.4 GHz band in 2018. Prices per block were between £37 million and £39 million in the allocation phase of the auction. Winning bidders tended to bid rather aggressively in the assignment phase. For example, EE/BT bid £50 million for its preferred assignment at the top of band. 3UK bid just over £25 million to locate its 20 MHz adjacent to its existing 20 MHz at the top of the lower segment of 3.4 GHz spectrum. Vodafone placed a bit for over £13 million. Only O2 bid modestly in the assignment round, but one might justify this based on O2's larger allocation phase revenues from winning the entire 2.3 GHz spectrum. In sum, both 3UK and BT/EE bid approximately 17 percent in assignment relative to their allocation phase expenditures—a significant amount. At least some of the aggressive bidding in 3.4 GHz assignment would be due to the fractured nature of the band. By accommodating rivals in allocation (which lowers revenues) assignment became more important.
Looking forward, Ofcom has a decision to make. By continuing with a fractured band in 3.6 GHz it could (potentially) encourage weaker competition in the allocation phase of the auction but more aggressive bidding in the assignment phase. Alternatively, Ofcom can rationalize the band and reduce some of the most harmful uncertainty arising from the assignment phase. This would likely result in a more competitive allocation phase of the auction as bidders acquire positions allowing them to better service customers with faster 5G products, knowing that assignment discontiguity will not be a concern.

[12] The relocation cost model need not be complicated. The starting point can be a linear combination of the factors affecting costs, with the coefficients on those factors representing the marginal effect that the factors have on relocation costs.

remains, minimizing the number of incumbents that must move their current holdings would effectively minimize relocation costs.

The proposal is structured as follows. We first describe the first-best mechanism—that is, one that guarantees contiguity and minimizes relocation costs while also reimbursing incumbents for those relocation costs. We then address the possibility that Ofcom cannot employ the first-best mechanism because it lacks the legal authority to make net payments to auction participants. We present alternative mechanisms that are also based on minimizing relocation costs but with modifications to ensure that no bidder has net negative auction payments. Finally, we discuss alternatives that Ofcom can employ in the absence of a cost model.

3.3.1 The Basic Relocation Cost Minimization Mechanism

We recommend a simple assignment mechanism that does not involve bidding. The idea is to agree upon relocation costs for any particular incumbent from any particular assignment. One can then choose the set of assignments that rationalizes post-auction holdings while minimizing those costs. The following notation will aid in the exposition of this mechanism:

- N = {BT, 3UK, VF, TF, Ofcom}: the incumbent holders of spectrum
- x_i = assignment of incumbent i's current holdings: a binary vector the length of the number of channels in the band; representing assignments with ones and non-assignments with zeros
- a_i = an assignment of i's post-auction holdings
- $C(x_i,a_i)$ = the relocation cost for incumbent i with current position x_i to move to assignment a_i: formula to be determined by Ofcom in consultation with incumbents based on the way relocation costs accrue

The procedure is to find the winning assignment, a*, that minimizes total relocation costs while satisfying the following constraints:

1. each incumbent is assigned one channel for each block in its post-auction allocation
2. no two incumbents are assigned the same channel
3. all assignments are contiguous (including Ofcom's unsold lots, if any, or lots won by an entrant)[13]

Under this preferred mechanism, each incumbent i would receive a discount against its auction payments according to its share of the minimized total relocation costs. That is, each incumbent's auction payments would be reduced by $C(x_i,a_i^*)$ to relocate to the assignment a_i^*. The economic logic motivating this mechanism is that it insulates the allocation stage from distortions arising from

[13] We assume Ofcom's post-auction holdings (in the form of unsold blocks, if any exist) should also remain contiguous. This assumption can easily be relaxed. Also note that this mechanism does not treat new entrants differently from incumbents. A new entrant is also guaranteed contiguity. However, that new entrant would not incur relocation costs, because it has no current assignment to relocate.

uncertainty about the assignment stage. Knowing they are guaranteed contiguous assignments, reimbursed relocation costs, and no assignment price, bidders can bid more aggressively in the allocation stage, spending the money they would otherwise reserve for potential relocation costs or assignment fees. Due to the tendency for bidders to reserve a budget to cover the worst possible assignment stage outcome as well as the fact that total relocation costs will be minimized, in expectation this mechanism should net greater total auction and social value than one that allowed such distortions.

3.3.2 A Constrained Cost Model that Forbids Net-Positive Payments

The pure cost-based mechanism described above could require Ofcom to have legal authorization to make net-positive payments to some incumbents at the end of an auction. For example, under the basic assignment mechanism, an incumbent could receive a payment from the auction if that incumbent did not acquire any new spectrum in the auction (of the 3.6 GHz product or any other product, such as 700 MHz, in the same auction) but was still required to relocate its frequencies. Given the possibility that Ofcom may not have legal authority to make such payments, an alternative would be to implement the cost-model approach but to deny net positive payments. We discuss this approach here, but we also note that given the increasing need for band-restructuring auctions worldwide, Ofcom could see the 3.4-3.8 GHz band as an opportunity to seek legal approval to make payments in an incentive auction sense.

The simplest approach to denying any net-positive payments is to let $C(x_i,a_i^*)$ be the *maximum* discount available to bidder i, which can only be applied one-for-one against bidder i's positive auction payments. In the event that the full discount would result in a net negative auction payment, the discount would be decreased to the level that makes the net auction payment zero. So, bidder i's net payment would be $min\{P_i - C(x_i,a_i^*), 0\}$, where P_i represents bidder i's positive auction payments, e.g., from acquiring spectrum or assignments in other bands.

This alternative preserves the property of the basic model that bidders do not make assignment payments. Bidders are guaranteed to make nonnegative net payments as a result of reducing the discount they receive. Note that this modification of the mechanism could encourage incumbents to bid more aggressively in the allocation stage in order to avoid any reduction to their relocation cost discounts.

3.3.3 Relaxing Full Contiguity in the Cost Model

There is at least one extension to the basic cost model mechanism that Ofcom might consider. Specifically, Ofcom might allow incumbents the option to relax constraint (3) – the constraint requiring full contiguity – as it applies to themselves. For some incumbents, this could reduce their own relocation costs when complete contiguity is not crucial and relocation costs exceed positive auction payments, that is, when $P_i - C(x_i,a_i^*)<0$. For example, suppose an incumbent such as 3UK does not acquire new spectrum (and therefore has no positive payments to offset with its relocation cost discount). With 140 MHz in post-auction holdings, 3UK could choose to relax constraint (3) so that it is only guaranteed a minimum of 100 MHz of contiguous spectrum. Doing so would likely lower 3UK's total relocation costs under the cost-based assignment mechanism, which would result in a net savings for 3UK given that

Ofcom lacks the authority to make net positive payments. Hence, this decision would constitute a form of assignment stage bidding, where, prior to the minimization of relocation costs, each bidder has the opportunity to declare the minimum size of their maximum contiguous assignment.

Ofcom could also make such a decision on behalf of all bidders, so that certain types of discontiguous assignments would be generally permitted. For example, Ofcom could decide that so long as each bidder achieves contiguity for, say, 100 MHz of spectrum, any additional bandwidth could be assigned in a separate block. As mentioned above, this could apply to 3UK, but it could also apply to Vodafone, for example, were it to acquire more than 50 MHz in the 3.6 to 3.8 GHz auction. And it would apply to BT or O2 were either to acquire more than 60 MHz.

3.4 Alternative Assignment Mechanisms without a Cost Model

While the relocation cost-based approaches described above are preferred, we recognize the possibility that the consultation process fails to produce a relocation cost model. Here we discuss three mechanisms that do not involve a cost model. The first is based on bidding with tokens and is our recommended method because it minimizes uncertainty about excessive assignment pricing. We also discuss the standard Vickrey mechanism and a variant that allows negative bids and assignment payments to bidders.

3.4.1 Bidding with Tokens

Under our preferred mechanism, assignment stage bidding is done with "tokens" instead of real money. That is, each bidder is allowed to submit a bid between zero and 100 tokens for every assignment stage bid option. The bids are not restricted in any other way. Notably, there is no "budget" condition here that applies to the sum of a bidder's individual bids. That is because a bidder can win one assignment at most. Therefore, the only relevant budget condition is the one that applies to individual bids, i.e., no individual bid can exceed 100 tokens.[14] With the token bid amounts, Ofcom runs the usual winner determination problem, maximizing the sum of bids for winning assignments. However, there is no need for the additional step of calculating Vickrey prices when bidding with tokens.

The appeal of this mechanism is that it controls for two of the three sources of uncertainty about the assignment stage that have distortionary effects on allocation stage bidding: split assignments and excessive assignment stage pricing. However, without a relocation cost model that can be used for relocation cost minimization and reimbursement, bidders will still face uncertainty about relocation costs. Furthermore, because the budget condition is the same for every bidder, 100 tokens, the mechanism has no way to account for the tradeoffs between an incumbent trying to avoid worst-case relocation costs of £100 and another incumbent trying to avoid worst-case relocation costs of £100,000.

[14] The mechanism would technically allow a bidder to submit separate bids of 100 tokens for every one of its bid options (although this is not recommended because such a bid would express indifference between all options).

3.4.2 Vickrey Mechanisms

Because of how common they are in spectrum auctions, we also discuss Vickrey assignment stage mechanisms for use in the absence of a relocation cost model. Under the standard Vickrey mechanism, post-auction spectrum holders would bid for specific assignment options deemed "feasible" by Ofcom. All feasible assignment options should respect constraints (1)-(3) given above. However, Ofcom may relax constraint (3) if it is determined through consultation with incumbents and other potential bidders that contiguity beyond some threshold, e.g., 100 MHz, is unnecessary. It is important to note, however, that this conventional assignment stage mechanism will likely have distortionary effects on the allocation stage, even if the set of feasible assignments is restricted to contiguous ones. This is because bidders will still withhold spending in the allocation phase as a hedge against excessive assignment stage pricing and their worst possible relocation costs.

A variant of the standard Vickrey mechanism allows for negative bids, so that incumbents can receive payments instead of making payments for certain assignments. This is appealing for the 3.4-3.8 GHz band where incumbents have already paid for frequencies once and would prefer reimbursements for relocating the second time around. The key is to have a budget condition that applies across all of the incumbent's bids, i.e., the sum of an incumbent's bids across its assignment bid options must be nonnegative.[15][16] This is to prohibit the obvious strategy of bidding large negative values for every option, knowing that every bidder must be assigned something.[17] The winner determination problem would, as usual, find the feasible assignments that maximize the sum of winning bids. However, even with the budget restriction, the maximized sum of winning bids could still be negative. There are potential ways to work around this problem, but those fixes can be complicated, distortionary, and subject to gaming.

As a final note, when used in conjunction with a Vickrey pricing rule, this mechanism will never result in incumbents receiving payments even when their winning bids are negative. This is because Vickrey prices are based on the opportunity cost of each bidder's winning assignment, which is always nonnegative. Therefore, for this mechanism to work as intended, it must employ a different pricing rule, such as the first price rule. Employing a first price rule comes with the usual caveat, i.e., it encourages gaming and bid shading.

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[15] Note that it does not make sense to allow entrants to make negative bids, since they do not have relocation costs.

[16] Ofcom may contemplate an additional restriction in the form of a minimum negative bid amount that incumbents can submit for any assignment bid option. The purpose of this would be to control the range of outcomes so that no incumbent is subsidized beyond some "reasonable" amount by the other bidders. Determining what minimum amount is reasonable would be a matter of determining the greatest relocation costs an incumbent could incur.

[17] With this mechanism, it is crucial that all assignment bid options are feasible. Otherwise, the budget condition does not generally hold and can also distort preferences.

4 An Aggregation Limit in 3.4 GHz

We assume that Ofcom will impose some sort of spectrum aggregation limit within 3.4 to 3.8 GHz. If so, a limit of 140 MHz applied to the entirety of the 3.4-3.8 GHz range could be one sensible alternative. 140 MHz is justified in that 3UK already holds 144 MHz within the band, and as part of band rationalization, 3UK might be willing to divest 4 MHz of spectrum while achieving contiguity. Consequently, there would be a reasonable expectation that, in a competitive auction scenario, the 140 MHz limit would apply solely to 3UK.

Under a 140 MHz aggregation limit, one must discern whether and how to credit 3UK for the 4 MHz of spectrum it would divest. One might argue that the benefit of (at least) 100 MHz of contiguous spectrum should be sufficient to induce 3UK to divest itself the superfluous bandwidth. And given that auction revenues will likely be used to set 3UK's annual licensing fees in the band, 3UK should have incentive to divest itself of some marginal amount of spectrum that could lessen a supply constraint.

This said, Ofcom could set a credit at auction prices for 3.6 GHz toward 4 MHz of divested spectrum. The credit could be applied after the auction to any additional spectrum (in 700 MHz) that 3UK were to win. One straightforward method would be to apply the revealed prices of 3.6 GHz spectrum (or the best estimate of them given the auction design) to the 4 MHz of spectrum. Or given that the 4 MHz of spectrum would be potentially located anywhere in the 3.4 to 3.8 GHz band, a blending of prices in the 3.4 GHz and 3.6 GHz band could be used. This method could be desirable should Ofcom prefer a more complex design for the 700 MHz and 3.6 GHz bands (such as CCA) in which specific price data for specific spectrum blocks may not be available.

5 A Voucher System

As an additional option to create an even more efficient auction, we include here a proposal for a voucher system that could be included or omitted without substantially changing the details of the proposed framework. The voucher system would enable a complete restructuring of the 3.4-3.8 GHz band by allowing incumbents to not only increase their holdings by acquiring Ofcom's unallocated spectrum, but also to decrease their holdings when there is sufficient demand from competitors to cover the additional supply. For example, suppose total incumbent holdings are 274 MHz and unallocated spectrum is 116 MHz. Then, 3UK could decide at any point during the auction to reduce its holdings from 144 MHz to 120 MHz as long as the total demand from the rest of the bidders, including existing holdings, was at least 270 MHz. Reducing its holdings in this way would entitle 3UK to a payment equivalent to 24 MHz (or 2.4 blocks at 10 MHz/block) at auction clearing prices. Allowing bidders to increase and decrease their holdings in response to market prices gives the market more freedom in finding an efficient allocation for the entire 3.4-3.8 GHz range as well as any other bands simultaneously auctioned.

This voucher system is very similar to what the FCC has proposed for the US 37/39 GHz band.[18] However, in the UK, its implementation would be even simpler. The UK has only nationwide incumbent licences, whereas vouchers in the US must be calculated and applied by geographic licence area. The US bandplan is also plagued by encumbrances that make the calculation of vouchers more complicated than would be the case in the UK. Overall, these factors mean that the implementation of the framework in the UK would be even simpler than in the US.

The voucher system works by issuing incumbents vouchers for the value of their current holdings. Vouchers could be expressed in MHz or in numbers of blocks in the new bandplan. Assuming 10 MHz blocks, voucher positions based on current holdings would be:

- BT would receive 40 MHz or 4 blocks worth of vouchers.
- Vodafone would receive 50 MHz or 5 blocks worth of vouchers.
- Telefonica would receive 40 MHz or 4 blocks worth of vouchers.
- 3UK would receive 144 MHz or 14.4 blocks worth of vouchers.[19]

The voucher is purely a financial instrument; it does necessarily lock an incumbent into a spectrum position. It is used to determine payments at the end of the auction based on the difference between vouchers valued at auction clearing prices and actual auction winnings.

- If an incumbent wants to maintain its pre-auction spectrum holdings, that incumbent would merely maintain a level of demand equal to its voucher position in the auction. If the auction finished with the incumbent demanding its voucher position, the incumbent would win blocks equivalent to its voucher position and owe nothing in the 3.4-3.8 GHz segment of the auction.
- If an incumbent wanted to increase its spectrum holdings, it would express demand above its voucher position. If the auction finished with the incumbent demanding more than its voucher position, then the incumbent would be required to pay for that additional amount of spectrum at auction clearing prices.

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[18] See *Use of Spectrum Bands Above 24 GHz for Mobile Radio Services*, GN Docket No. 14-177, Fourth Further Notice of Proposed Rulemaking, FCC 18-73 (August 3, 2018). This proposal is based on prior work by Bono, J. and Ingraham, A., "An Auction Design for Millimeter Wave Spectrum," Attachment to Letter from Alex Starr, Assistant Vice President, AT&T, to Marlene H. Dortch, Secretary, FCC, GN Docket No. 14-177 et al., at 2, Attach. at 3-5 (filed Dec. 12, 2017) (AT&T Dec. 12, 2017 Ex Parte). For an earlier description of a similar mechanism, see also, FCC, OPP Working Paper Series #38, November 2002. Kwerel and Williams, "A Proposal for a Rapid Transition to Market Allocation of Spectrum." https://apps.fcc.gov/edocs_public/attachmatch/DOC-228552A1.pdf

[19] Ofcom has a choice whether to include 3UK's final 4 MHz in its voucher position or to round it down to 140 MHz/14 blocks. Note that 3UK would not be allowed to bid on a fractional number of blocks in the auction. It could "sell" the fractional position to win 140 MHz and be compensated at 40% of the auction clearing price for the 4 MHz it sells. Or it could apply the fractional position towards a position of 150 MHz, where it would owe an additional payment of 60% of the auction clearing price for the extra 6 MHz it acquired. On this last point, note that we propose a spectrum aggregation limit below that would prohibit any bidder from acquiring more than 140 MHz. Under this proposal, 3UK would be required to receive compensation on at least 40% of a 10 MHz block at auction clearing prices.

- Finally, if an incumbent wanted to reduce its spectrum holdings below its voucher position, it would express that lower level of demand in the auction. If the auction finished with that incumbent demanding less than its voucher position in 3.4-3.6 GHz, then the incumbent would receive an incentive payment for the difference between its starting voucher position and its final winning demand at auction clearing prices.

The last point is the crucial advantage of the voucher system. By allowing spectrum to change hands from one incumbent to another bidder at auction clearing prices, the voucher system allows an efficiency-enhancing reallocation of the band while respecting incumbent holdings.

Vouchers could also be used to cover the costs of spectrum winnings in other bands let in the same auction. For example, if 700 MHz spectrum is available in the same auction, then incumbents should be able to use any surplus vouchers to offset the cost of 700 MHz spectrum winnings. For example, an incumbent with 140 MHz of vouchers might decide at any point during the auction that it only wants 100 MHz of 3.4-3.8 GHz. Perhaps because relative prices favor 700 MHz, that incumbent would prefer to use the remaining 40 MHz to offset an acquisition of 700 MHz. Assuming 3.4-3.8 GHz clearing prices at £100 for 10 MHz, the incumbent would have up to £400 to apply towards its payment obligation in the 700 MHz band.[20]

With the voucher system in place, the auction supply expands to the entire 390 MHz of the 3.4-3.8 GHz band. Each incumbent's initial bid for the 3.6 GHz product must be a minimum of its voucher position and a maximum of the total supply. In every round thereafter, bidders may place bids in any amount within the constraints that normally apply to generic SMR and uniform-price clock auctions, including activity rules and no-excess supply rules. It is important to note that a no-excess supply rule would limit the ability of an incumbent to demand less of the 3.6 GHz product than its voucher position. In the extreme case, where the 3.6 GHz category never had excess demand from the outset, no incumbent could win less than their voucher position.

Finally, the voucher system described here requires a generic SMR or uniform-price clock auction design for the allocation stage. A CCA design is ill-advised for a voucher system due to the complications that arise in handling the uncertainty about potential excess supply.

[20] If Ofcom does not have the legal authority to make net positive auction payments, the voucher system can still be used. When requesting to reduce demand in the 3.6 GHz segment, incumbents would do so knowing that vouchers will only be applied up to the point that they do not create net positive auction payments from Ofcom.