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The case for spectrum caps that support efficient and pro-competitive outcomes in the award of PSSR spectrum

NERA Economic Consulting

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1. Executive summary

NERA Economic Consulting, with the support of Professor William Webb, has been asked by Telefonica UK[1] (O2) to analyse the relationship between holdings of mobile spectrum, the efficiency of spectrum use and competition in the downstream market, with particular focus on potential market outcomes following the PSSR award. Based on this assessment, we consider the competition measures proposed by Ofcom for the PSSR award. In its November 2016 Consultation Document[2], Ofcom proposes a global cap of 255 MHz on immediately usable spectrum. We find that this measure is insufficient to preclude potential award outcomes that could reduce competition, choice and quality of service for UK consumers. We propose instead that Ofcom adopts variants of its proposed Options B and C, including caps on usable spectrum in each relevant time period and additional band specific caps, which if implemented together are more likely to facilitate outcomes that promote efficient use of spectrum and downstream competition.

Ofcom has a unique mandate to address efficiency and competition concerns associated with the allocation of spectrum, so as to maximise welfare for consumers

Broadly, spectrum has the potential to generate three types of welfare benefits:

- *Static efficiency gains*. Spectrum can be deployed to enhance the quality of service in provision of existing mobile services. It may also be a more cost effective and practical alternative to investment in physical network infrastructure. Improved quality of service and lower costs generate increased welfare for both network operators and their customers.

- *Dynamic efficiency gains through innovation*. Spectrum may be used by mobile operators to deploy innovative new services that realise a whole new set of welfare benefits for consumers over-and-above those realised through existing services. 5G deployment may fit into this category.

- *Dynamic efficiency gains through competition*. The downstream market for mobile services is highly competitive. Competition between operators imposes discipline on operators to deploy spectrum efficiently, invest in quality of service enhancements and pass cost savings on to consumers through lower prices. This competition realises additional welfare benefits for consumers.

The focus in this report on both efficiency and competition is deliberate and important. Ofcom is the only body responsible for assigning spectrum in the UK, and the only one charged with promoting the efficient use of spectrum. As we describe in Section 2, this means that Ofcom has a unique ex-ante responsibility to ensure that spectrum is allocated to the users that can generate the highest welfare for consumers. Ex-ante powers are particularly

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[1] Telefonica UK Limited operates under the brands O2 and giffgaff and provides wholesale access to a number of MVNOs including Tesco Mobile, Lycamobile and soon Sky and TalkTalk. It is referred to hereafter as “O2”.

[2] Ofcom, Award of the 2.3 and 3.4 GHz spectrum bands, 21 November 2016. It is referred to hereafter as “the Consultation” or “CD”.

important because the scope for ex-post re-assignment of spectrum is limited, as (a) there are structural barriers to efficient trades occurring between major operators; and (b) ex-post regulatory intervention is unlikely, as the burden of proof necessary to support the forced sale of an asset is (appropriately) high.

Ofcom is quite right to be focused on competition, but not to the exclusion of other sources of welfare gain for consumers. A theme throughout this response is our concern that Ofcom is overlooking the potential for huge losses in static welfare benefits for the customers on networks that become spectrum constrained. This, in turn, has led Ofcom to underestimate the risk to the broader UK economy posed by the current grossly asymmetric assignment of spectrum, and to underestimate the extent of remedies required to make certain that this situation is not perpetuated for the next five years.

The PSSR award could have a huge impact on the UK mobile market

The outcome of the PSSR award may play an outsize role in determining the efficiency and competitiveness of the UK market over the coming years. Simply put, [✂] REDACTED and this auction provides the only realistic source of capacity to address this problem. At the same time, as Ofcom makes clear in the Consultation, EE (owned by BT[3]) and Vodafone are sitting on a large volume of unused prime mobile spectrum. As we set out in Section 3, this highly asymmetric distribution of mobile spectrum resulted from the flawed outcome of the UK 4G auction, compounded by merger decisions that ignored spectrum allocation concerns, on the assumption that they could be addressed through future primary awards.

The asymmetry in spectrum holdings between UK operators is exceptional and should be a cause for alarm

There is nothing normal about the asymmetry in spectrum holdings in the UK. In Section 4, we compare the holdings of UK mobile operators with their peers worldwide. This reveals that just 18 of 320 operators across 100 countries have shares of usable spectrum[4] at 15% or below, and two of these are in the UK (O2 and H3G). Amongst European operators that launched before the 3G era, O2 is alone in having a spectrum share below 20%. O2 also has the lowest ratio of spectrum share to subscriber share worldwide in our survey of 320 operators. Meanwhile, EE has a usable spectrum share of 45%, the second highest level in Europe, despite many other markets having only three operators.

Such extreme asymmetry in distribution of an essential resource for provision of mobile network services should raise concerns regarding the efficiency of spectrum use and potential for sustainable four-player competition in the UK market. There are good reasons for Ofcom to be more concerned about spectrum allocation now than in the past, as exceptional growth in consumer demand for 4G data is placing unprecedented pressure on mobile networks.

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[3] BT acquired EE in 2016. In this report, if we refer to EE in a post-acquisition context, we mean the combined entity, which Ofcom refers to as BT/EE in the Consultation.

[4] We define usable spectrum as 450 MHz, 700 MHz, 800 MHz, 850 MHz, 900 MHz, 1800 MHz / PCS, 2100 MHz / AWS (all FDD), 2600 MHz (FDD and TDD), and 2300 MHz (TDD). We exclude 1400 MHz, as the handset ecosystem is not yet mature, and 1900 MHz TDD holdings, as the ecosystem path for this band is not yet clearly established. MNOs with less than 4% subscriber share are excluded.

Spectrum is the only viable solution to capacity constraints

In the Consultation, Ofcom expresses the hope that operators with low spectrum shares can compensate for a lack of spectrum through investment in new sites and improved technology. To some extent, this is already happening. For example, O2 has led the way in refarming of spectrum, and migration of customer devices from 2G and 3G to more efficient 4G technology. However, as we explain in Section 5, going forward, the scope for operators to build their way out of capacity crunches without new spectrum is limited. This reflects the difficulty and expense of accessing new urban sites, and technology performance issues when densifying 4G networks if re-using the same frequencies. Fortunately, the PSSR bands at 2.3 GHz and 3.4 GHz can provide a solution. The most critical development here is the maturing of new technology solutions, such as MIMO and directional antennas, which – contrary to past expectations – make it viable to deploy 3.4 GHz as a 4G capacity band, based on a macrocell grid.

The best way to prepare for 5G is to address constraints on 4G provision

Historically, new generations of mobile technology have provided significant capacity gains through improved technical efficiency and use of new frequency bands. Within Ofcom's consultation, there appears to be an implicit expectation that 5G will be important in enhancing network capacity and that the PSSR award should be crafted to facilitate its emergence. However, in Section 6, we show that 5G is likely to differ in its form and its method of introduction compared to previous generations: the optimal route to deploying 5G is, almost certainly, via rapid availability of 3.4 GHz for 4G solutions which can subsequently evolve to 5G. Many of the broader opportunities that are associated with 5G, such as network function virtualisation and Internet of Things (IoT) support, will be delivered first as part of 4G evolutions before 5G radio technology arrives.

We also address the view that 5G deployment might need 100 MHz carrier bandwidths. We show that the consumer demand for associated data rates does not yet exist, that the same consumer speeds could be achieved with carrier aggregation of 20 MHz channels, and that equipment to utilise broad channels will not be available until after 2020. We also point out that there are other viable routes to delivering 100 MHz carriers after an auction, such as spectrum sharing or spectrum swaps. Hence, we conclude that the best way to support development of 5G is to prioritise use of PSSR spectrum to alleviate 4G capacity constraints, and policy should not be distorted to accommodate the unrealistic idea that a single carrier might launch an early 5G network using a large block of 3.4 GHz spectrum.

Ofcom should consider the impact of PSSR award outcomes on UK consumers from both an efficiency and competition perspective

Against this background, we believe that Ofcom can best fulfil its statutory duties by analysing the impact of potential outcomes to the PSSR award from both an efficiency and competition perspective. We present our own assessment in Section 7. It is important that efficiency and competition be considered side-by-side, as they inform each other. For example, if it can be demonstrated that an auction outcome is obviously inefficient, then intervention to preclude it is essentially costless, which may in turn may short-circuit a more challenging discussion of whether the associated competition arguments are sufficiently certain to justify intervention. To support our analysis, we make use of a high-level valuation model that considers the impact of spectrum-induced capacity constraints on the four operators and on consumers. It is based on sufficient assumptions to identify outcomes that are clearly not supported by an intrinsic business model but may be supported by strategic investment value. A key point here is that it is not necessary for Ofcom to engage in detailed cost modelling of mobile networks (which it is on record as saying is difficult) in order to identify obviously bad outcomes and draw conclusions regarding reasonable remedies.

Adequate network capacity is the key dimension linking spectrum allocation to consumer welfare

We begin our assessment with an analysis of the dimensions that link the allocation of PSSR spectrum to welfare creation. Here, we borrow from Ofcom's June 2012 competition assessment but update its dimensions to reflect spectrum use in 2017. We identify sufficient data capacity as the critical dimension in driving welfare creation through spectrum use. Other dimensions, such as peak data speeds and 5G readiness are likely to have only a minor impact on welfare creation over the next five years.

Capacity constrained networks can be expected to compete less vigorously for customers and may cease to be credible competitors for customers that place a high value on reliable network performance. This, in turn, may allow unconstrained networks to charge higher prices. In the worst case, a congested network may suffer a consumer backlash that greatly diminishes its brand value and reduces its credibility across the entire market. The competition effects may be enduring – given that customers appear sluggish in moving away from under-performing networks, then can expected to be equally sluggish in recognising opportunities to return to those networks once they recover their performance.

The Consultation leaves us somewhat confused regarding Ofcom's position on the relative importance of capacity, peak speed and 5G readiness. On the one hand, at CD §4.115, Ofcom says that "*for at least the next few years, we consider it is only in terms of capacity and coverage that there are necessary minimum components which an MNO will need to be credible*". This position is closely aligned with our analysis. On the other hand, Ofcom cites the possibility that more spectrum may make Vodafone a more effective competitor to EE as justification for placing no restrictions on its ability to bid for 2.3 GHz (CD §5.60), and it prioritises (unrealistic) benefits of 5G readiness over 4G capacity in its choice of remedies for 3.4 GHz (CD §5.74).

PSSR spectrum is a unique source of additional capacity for two transition periods, from 2017-18 and 2019-20

Next, we consider the timelines over which Ofcom needs to assess efficiency and competition effects. We identify three periods for analysis:

- a first transition period (TP1), from 2017-18, in which 2.3 GHz is the only new usable spectrum;
- a second transition period (TP2), from 2019-20, when 1400 MHz and 3.4 GHz will be usable; and
- a longer-term period from 2021 when other bands will become available.

The key difference between our analysis and Ofcom's work is the identification of the second transition period. We anticipate a period of two years or more between availability of 3.4 GHz and other bands, namely 700 MHz and 3.6 GHz. This is important because the quantity of new spectrum available at 2.3 GHz is too small to address data capacity concerns beyond the short term, with the implication that 3.4 GHz will become an essential resource for adding incremental 4G capacity from 2019. Indeed, the 3.4 GHz band is likely to be more important for provision of 4G services in the UK than in other European markets because two operators have unusually weak spectrum holdings across lower frequency bands.

Without intervention, there is a real risk of an award outcome that reduces competition and imposes welfare costs in excess of £5 billion

Using our valuation model, we then explore the potential for the PSSR spectrum to generate welfare for UK consumers through static efficiency, dynamic innovation and competition:

- **Static efficiency.** We present evidence that congestion owing to lack of spectrum is already [✂] REDACTED. To quantify the impact, we calculate intrinsic values to operators from avoiding subscriber losses owing to capacity constraints by adding spectrum in 10 MHz blocks. We then identify the value premium to operators from acquiring spectrum in TP1 (2.3 GHz) and TP2 (3.4 GHz) as opposed to the longer term (700 MHz or 3.6 GHz). We observe that [✂] REDACTED. Furthermore, O2 and H3G are the only operators to place an intrinsic value premium on spectrum that can be deployed before 2020.

  We use these results to model the **welfare impact** on consumers of PSSR award outcomes in which O2 and H3G fail to win sufficient spectrum to alleviate their capacity constraints. We make assumptions about the loss in value to customers who remain on congested networks and the forced switching costs for those who move network but would otherwise have stayed. We calculate that up to £5.4 billion of consumer welfare is at risk if O2 and H3G do not secure an efficient allocation of PSSR spectrum.

- **Dynamic innovation.** We consider whether the PSSR spectrum could also realise additional benefits though supporting the launch of innovative new services under the 5G banner. We think this will be the case, although benefits over the next five years will come from advanced 4G services, with benefits from 5G materialising after that, when other spectrum options will be available. We disagree with Ofcom that there is a benefit to allowing every operator to compete for a block of 100 MHz or more at 3.4 GHz. Indeed, given the likelihood that there will ultimately be a converged 4G-5G ecosystem, we identify the possibility that EE could further increase its spectrum share by buying a large block of 3.4 GHz spectrum as a potential long-term barrier to the diffusion of innovation benefits across UK operators and their customers.

- **Competition.** We explore the role of the PSSR spectrum in shaping the competitive landscape in mobile through each of our time periods. First, we summarise the relevant academic literature, which links capacity constraints to a softening of price competition. Second, we identify leading indicators of reduced competition in the UK mobile market, including recent evidence of market bifurcation and price increases for high-end data services. Third, we extend our valuation model to explore the potential magnitude of strategic investment value for Vodafone and EE from securing sufficient PSSR spectrum to block O2 and/or H3G from alleviating capacity constraints across our two transition periods. We show that these values are very large and, if crystallised in bids, could lead to Vodafone and/or EE inefficiently blocking O2 and H3G from winning spectrum at both 2.3 GHz and 3.4 GHz.

Our analysis of intrinsic value demonstrates that there are some obviously undesirable outcomes to the PSSR auction from a welfare perspective. These include any outcomes where: O2 or H3G are blocked from winning 2.3 GHz spectrum; or O2 and H3G do not win additional spectrum at 3.4 GHz. Our analysis of competition effects reveals that the strategic investment value for Vodafone and for EE from blocking rivals is sufficiently large that such outcomes could happen. Whether or not it is likely that Vodafone or EE will bid in such an aggressive manner is beside the point. Given that downside costs of action to prevent such outcomes are small, Ofcom should act to eliminate them, whatever its views on the likelihood of them happening in practice. Having made the argument in 2015 and 2016 that the UK should remain a four-player market, it is beholden on Ofcom to ensure that lack of access to spectrum does not prevent an operator from remaining a credible player.

Tougher competition measures are required to eliminate the risk of undesirable PSSR award outcomes

In Section 8, we set out our views on the competition and other measures proposed by Ofcom. We strongly support Ofcom’s choice of format and detailed rules, including its proposals to further constrain withdrawal rules, but these measures cannot by themselves address the risks to efficiency and competition identified in this report. With respect to competition measures, we agree that Ofcom has broadly identified the appropriate range of options, given scope for modification. However, Ofcom’s preferred Option A is not a strong enough measure to prevent the possibility of a very inefficient and anti-competitive award outcome.

Option A leaves open the possibility that one bidder (Vodafone) could block all constrained bidders from securing 2.3 GHz spectrum, and does nothing to address capacity concerns in TP2. Ofcom’s preference for Option A over Option C is also based on the potential benefits from EE using a huge swathe of 3.4 GHz to launch early 5G services, but our analysis indicates that such benefits are illusionary.

Throughout its analysis, Ofcom weighs the risk of being too “interventionist”. This bias against intervention may serve it well in many other policy situations but it is inappropriate here. Our efficiency and competition assessment demonstrates that downside risks from being too interventionist are much smaller than the downside risks associated with an inefficient outcome in which O2 and H3G are blocked from winning essential spectrum. Nevertheless, we recognise that a degree of pragmatism may be required with respect to competition measures. [✂] REDACTED. Thus, it is overwhelmingly in the interests of consumers that the award of 2.3 GHz happens as soon as possible. On this basis, there is a certain logic in Ofcom avoiding measures, such as a spectrum reservation (Option D) or very tight overall caps (Option E), that are likely to be contentious and hard to justify without Ofcom engaging in a much deeper and time consuming assessment of efficiency and competition. Our recommendation, based on modifications to Ofcom’s Options B and C, is a compromise. It eliminates the worst case outcomes but still gives more flexibility to EE and Vodafone than our assessment suggests is necessary.

We recommend the following competition measures:

1. **A 35% cap on usable spectrum,** to apply in both:
    (a) **TP1:** Current spectrum plus 2.3 GHz – so as to prevent EE from bidding for this spectrum.
    (b) **TP2:** Above spectrum plus 1400 MHz and 3.4 GHz – so as to prevent EE from bidding for very large packages in the 3.4 GHz band, and to make it less likely that EE and Vodafone could jointly block O2 and H3G.
2. **Two precautionary band-specific caps**:
    (a) **20 MHz per operator at 2.3 GHz** – as a symmetric measure across all bidders that precludes outcomes where one bidder (Vodafone) can block its rivals.
    (b) **100 MHz per operator at 3.4 GHz** – as a safeguard against future spectrum asymmetry in the (admittedly unlikely) case that having large blocks in the 3.4-3.8 GHz does emerge as an important factor in supporting 5G.

Ofcom may also consider other complementary measures to increase the likelihood of efficient allocation of PSSR spectrum. These include:

3. Committing now to undertaking an **in-depth review of the links between spectrum holdings and competition and efficiency** before the auction of 700 MHz and 3.6GHz;
4. Providing an **update on its plans for clearing and awarding 700 MHz and 3.6 GHz**; and
5. Setting out **an approach to defragmenting holdings in the broader 3.4-3.8 GHz band** in case this is beneficial for 5G after 2022.

These further measures would make it easier for operators to identify relative valuations for PSSR spectrum and other bands available later, and thus promote straightforward bidding based on intrinsic value.

2. Ofcom's duty to promote efficiency and competition

When regulators design auctions for mobile spectrum, they normally have two primary goals in mind: promoting economic efficiency; and supporting competition in the downstream market.

These two goals are closely related:

- An **economically efficient allocation** of mobile spectrum implies a situation in which every unit of frequency is optimally allocated to serve each individual or entity in the best way while minimizing waste and inefficiency.[5] A perfectly efficient allocation will result in the highest level of welfare possible flowing to the population at large.

- The **dynamic welfare benefits from enhanced competition** (or losses from reduced competition) associated with a particular allocation of spectrum should, by definition, be taken into account when assessing efficiency. Competition benefits are one of three types of welfare gain that contribute to efficiency, the others being the **static welfare benefits from enhanced provision of existing services** and **dynamic welfare benefits from innovation and new services**.

In the Consultation, Ofcom primarily focuses on the competition implications of particular spectrum allocation outcomes. However, it pays relatively little attention to the current or future efficiency of spectrum use across the four operators. To illustrate this point, we have constructed a word cloud of the Consultation, as shown in Figure 1: "competition" is one of the most frequent words used in the document, appearing over 500 times; whereas "efficiency" (and its synonym "efficient") are mentioned just 30 times.

Ofcom is quite right to be focused on competition, but not to the exclusion of other sources of welfare gain for consumers. We are concerned that Ofcom is overlooking the potential for huge losses in static welfare benefits for the customers on networks that become spectrum constrained. This, in turn, has led it to underestimate the risk to the economy posed by the current grossly asymmetric assignment of spectrum in the UK, and to underestimate the extent of remedies required to make certain that this situation is not perpetuated for the next five years.

In this section, we set out Ofcom's duties in relation to efficiency and competition in spectrum allocation, and highlight why it has unique responsibilities with respect to efficiency. We then explore the role of market procedures in delivering efficient outcomes and the risks of market failure. These subsections provide a framework for discussion of these issues in relation to the PSSR award throughout this paper.

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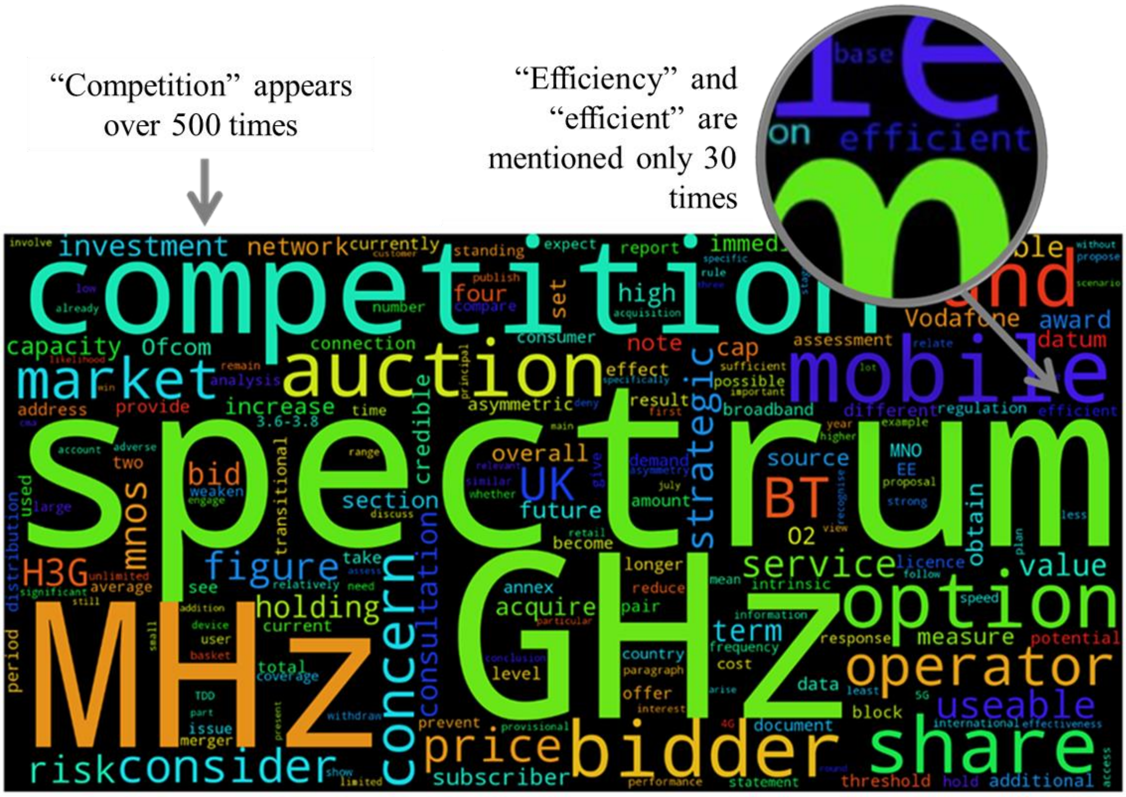
[5] For a good overview of the concept of economic efficiency, see: http://www.investopedia.com/terms/e/economic_efficiency.asp

Figure 1: Word cloud for the Consultation


"Competition" appears over 500 times

"Efficiency" and "efficient" are mentioned only 30 times

Source: NERA Economic Consulting. Figure constructed using Python 2.7 and the Wordcloud version 1.2.1.

2.1. Ofcom's unique role in promoting economic efficiency in spectrum allocation

Promotion of efficiency and competition are enshrined in both UK and European law, and are central to Ofcom's mandate to manage scarce spectrum resources on behalf of UK citizens. Ofcom is the only body responsible for assigning spectrum in the UK, and the only one charged with promoting the efficient use of spectrum.

As Ofcom stated in its October 2015 statement on the PSSR award:

> "*Our principal duties under Section 3 of the Communications Act 2003 are:*
>
> - *to further the interests of citizens in relation to communications matters; and*
> - *to further the interests of consumers in relevant markets, where appropriate, by promoting competition.*
>
> *In carrying out our functions, section 3(2) provides that we are required, amongst other things, to secure the optimal use for wireless telegraphy of the electromagnetic spectrum; and the availability throughout the UK of a wide range of electronic communication services.*
>
> *Section 3(4) requires us, in carrying out our functions, to have regard to certain factors as appear relevant in the circumstances, including the desirability of encouraging*

> *investment and innovation in relevant markets; and the desirability of encouraging the availability and use of high speed data transfer services throughout the UK.*
>
> *In performing our duty under Section 3 of furthering the interests of consumers, we must have regard, in particular, to the interests of those consumers in respect of choice, price, quality of service and value for money.*"[6]

These duties are very similar to its obligations under EU law, as defined in Article 8 of the Framework Directive:

> "*ensuring that users … derive maximum benefit in terms of choice, price, and quality*." (Art. 8(2)(a))
>
> "*ensuring that there is no distortion or restriction of competition to the benefit of consumers and promoting, where appropriate, infrastructure competition*." (Art. 8(2)(b))
>
> "*encouraging efficient use and ensuring the effective management of radio frequencies*" (Art. 8(2)(d))

Ofcom's responsibilities may be contrasted with the Competition & Markets Authority (CMA), which – like Ofcom – has a mandate to promote competition for the benefit of consumers but has no direct responsibility to consider the efficient allocation of resources. The CMA describes its role as follows: "*We work to promote competition for the benefit of consumers, both within and outside the UK. Our aim is to make markets work well for consumers, businesses and the economy*."[7]

For the CMA, the distribution of spectrum is interesting to the extent that it may create enduring barriers to effective competition. This is a relatively high bar, which may allow very inefficient distributions of spectrum to be created and to endure without intervention. It is unlikely that either the CMA or a Court would consider evidence that one party is using spectrum less efficiently than another as sufficient evidence to justify intervention; almost certainly, a clear competition rationale would also be required. They can also be expected to defer judgement on non-competition aspects of efficiency to Ofcom, as the subject-matter expert. For example, in the BT-EE merger decision, the CMA declined to address concerns expressed by third parties regarding the asymmetric distribution of the UK spectrum based on assurances from Ofcom that such concerns could be addressed through future spectrum awards.[8]

Thus, while Ofcom is one of several bodies looking out for the interests of consumers from a competition perspective, it is the only one concerned with the broader welfare benefits

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[6] Ofcom, Public Sector Spectrum Release (PSSR), Statement, 26 October 2015, paras. 2.7-2.10.

[7] Competition & Markets Authority, "What we do" statement at https://www.gov.uk/government/organisations/competition-and-markets-authority/about

[8] See §12.36 of the Competition & Markets Authority Report on the merger of BT Group plc and EE Limited. 15 January 2016.

flowing from spectrum use. More specifically, Ofcom has a unique ex-ante responsibility to ensure that spectrum is allocated to the users that can generate the most value for consumers.

2.2. The role of market procedures and risk of market failure

When one considers an economy at large, a state of perfect economic efficiency is clearly theoretical. However, when one considers the allocation of mobile spectrum in a market that can only support a limited number of mobile operators, then it becomes a potentially achievable goal. This said, given that society only has approximate tools for measuring welfare, it is unrealistic to think that a regulator could ever be certain that spectrum allocation is fully efficient, especially as the efficient allocation may change over time. For this reason, Ofcom – like most leading regulators worldwide – relies on market procedures to determine spectrum allocation for mobile: auctions for primary awards; and secondary trading.

The efficiency of market procedures is predicated on the assumption that willingness to pay for spectrum is a good proxy for the value that an operator can generate from using the spectrum, and thus the flow of welfare benefits to society as a whole. As a general principle, this is broadly accepted by regulators and operators worldwide. However, it is also widely understood that, without guidance, spectrum markets may fail to deliver an efficient outcome.

We highlight here four factors that could prevent efficient market allocation of spectrum:

1. *Anti-competitive behaviour*. If bidders anticipate anti-competitive benefits from blocking their rivals from accessing additional spectrum, then this may lead them to increase their valuation. Ofcom makes this point in the Consultation when it distinguishes between **intrinsic value** – the value without any strategic considerations – and **strategic investment value** – the incremental benefits from denying competitors (CD §4.162). For the PSSR award, in relation to both 2.3 GHz and 3.4 GHz, we think Ofcom has underestimated the risk of inefficient auction outcomes resulting from bids driven by strategic investment value, and should go further in defining remedies that reduce or preclude the likelihood of such outcomes (see Section 6.5.3). We're also concerned that this is a barrier to efficient spectrum trading, which reinforces the importance of having an efficient primary award.

2. *Bids not reflecting market value*. There are multiple reasons why bidders may fail to submit bids that appropriately reflect their intrinsic value. Two factors that can have an outsize impact on auction outcomes are strategic bidding and budget constraints. Spectrum auctions often feature complex rules which may create incentives for bidders to under or over bid relative to valuation, either in hope of winning spectrum cheaply or constraining rivals. If bidders are budget constrained they may face difficult choices regarding how to prioritise demand, and are vulnerable to buying too little spectrum. In Section 3, we present compelling evidence that these factors distorted the outcome of the UK 4G auction which contributed to the current exceptional asymmetry in spectrum allocation. We are concerned that Ofcom appears to be proceeding on the default assumption that its 4G auction was efficient, despite evidence to the contrary, and therefore has erroneously concluded that the current status quo of gross spectrum asymmetry could be an acceptable outcome for the PSSR award.

3. *Externalities.* There may be broader benefits to society from a particular use of the spectrum that are not reflected in potential revenues for operators. This is typically not a concern when operators are competing to offer the same use, in this case 4G services, but might be relevant if there was potential to deploy a new service. Ofcom has raised the possibility that an early launch of 5G services using a large block of spectrum at 3.4 GHz might offer broader benefits to the UK. We concur that 5G should be deployed at the earliest possible opportunity but we think that the need for a large block of spectrum to enable this is very unlikely, for reasons we set out in Section 0. More generally, we do not think that any particular measures are needed to ensure rapid deployment of 5G other than early spectrum availability for 4G. Therefore, we do not think that Ofcom should be much concerned with 5G-related externalities when setting remedies.

4. *Transaction costs*. High transaction costs may deter participation in markets, preventing efficient allocation. We do not see this as a major concern for UK spectrum auctions, where Ofcom can set rules to encourage participation and participation costs are broadly symmetrical. However, bargaining costs may be a significant barrier to efficient trades, especially given uncertainty over the option value of retaining excess capacity and concerns that sellers may have about enhancing the competiveness of rival operators.

We strongly support Ofcom’s use of auctions for primary awards. Ofcom lacks the detailed information necessary to make fine judgements over the exact allocation of frequencies to each operator, and an auction can provide that information. However, it does have the information needed to identify obviously inefficient outcomes that could destroy welfare for consumers and society at large. Accordingly, we also strongly support the prudential use of remedies, such as spectrum caps, to preclude undesirable outcomes which may result from the problems described above.

The case for intervention is greatest for awards where (a) a very large proportion of spectrum is being made available – as this may have a larger and more enduring impact on the market; and (b) the current distribution of spectrum is already highly asymmetric, and this is a source of concern regarding efficiency – as the potential for very bad outcomes increases. Both these factors are relevant for the PSSR award, which will add over 30% to the total stock of mobile spectrum, and where spectrum asymmetry between operators is arguably greater than any other country in the world (see Section 4). *Prima facie*, we would therefore expect Ofcom to take a more interventionist approach for this award than is typical for spectrum auctions worldwide. In fact, as we show in Section 4.2, its current remedy proposals are unusually lax by international standards.

Ofcom’s ex-ante powers are particularly important for the PSSR award because the scope for ex-post re-assignment of spectrum is limited, for two reasons:

1. *Structural barriers to efficient trades occurring between major operators*. In our previous submission, we presented evidence that the secondary market for mobile spectrum in the UK is not functioning as Ofcom envisaged. The market is too small and illiquid to support regular trading. MNOs prefer to sit on unused or underused spectrum, rather than risk giving their competitors a lift. This is unsurprising given the

small number of operators, and the knowledge that any gain in subscribers must come at the expense of rivals. In particular, [✂] REDACTED.

This is a global phenomenon: worldwide, there are few examples of trades between major MNOs, and almost no examples of MNOs selling spectrum to smaller rivals. When such major trades do occur, they are typically tied to a regulatory intervention (such as a merger condition) or occur because two companies have a mutual strategic interest beyond the exchange of cash. For example, if one considers a list of mobile spectrum trades over the last three years in the United States (the most active spectrum market), it is striking that all the deals between the big four MNOs involve spectrum swaps rather than outright spectrum sales, whereas most trades involving smaller entities involve cash deals.[9]

2. *Ex-post regulatory intervention is unlikely*. The burden of proof necessary to support the forced sale of an asset is (appropriately) high. For a court or competition body to impose such a remedy, there would need to be clear evidence of a competition problem that could not be remedied by other means. BT’s acquisition of EE is a case in point. As we set out in Section 6, it is obviously not efficient for EE to have such huge spectrum assets when other operators are chronically short of spectrum. However, it is also true that EE may eventually deploy all of its spectrum. Accordingly, it is unsurprising that the CMA decided to take no action when presented with Ofcom’s reassurance that it would address any future market failure through appropriate competition measures in spectrum awards.

There could be significant benefits now and in the future from UK operators trading spectrum, such that operators with small holdings can expand or to allow all operators to consolidate holdings within bands. However, this is unlikely to happen unless there is a mutual interest. If Ofcom wants to promote efficient trades between operators, it needs to address the gross asymmetry in spectrum between the operators. In the short term, it can only do this through remedies that force operators with large holdings to trade off their strategic desire to hold on to excess spectrum versus their interest in new bands being made available. Without intervention, our view is that trading will only work if O2 and H3G have sufficient spectrum that they can trade as strategic equals with EE and Vodafone. This does not require symmetry in spectrum holdings but it does require that all operators have sufficient spectrum to avoid a capacity crunch.

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[9] For further information, we refer Ofcom to: NERA, The case for pro-competitive measures in the UK award of PSSR spectrum, September 2016, Section 4.1.

3. The current distribution of UK mobile spectrum is highly asymmetric

The current assignment of spectrum across mobile operators in the UK is exceptionally asymmetric. The two operators with the largest holdings, EE and Vodafone, together control 72.5% of usable spectrum[10], while the other two operators, O2 and H3G, have less than 28% of spectrum between them. This is a marked change since early 2010, when the four largest MNOs had very similar spectrum shares. In this section, we present evidence that this asymmetry has not emerged through functional market competition. Rather, it is the result of a series of regulatory and competition decisions which assumed that future awards would address any problems, and a 4G auction that failed to deliver. This distinction is important, for two reasons. First, it underlines the point that Ofcom should not be relaxed about the current distribution of spectrum which, as we show later in this report, is highly inefficient. Second, it highlights the importance of the PSSR award as the only mechanism that can address undue asymmetry in the next 4-5 years.

With the benefit of hindsight, our view is that Ofcom – both in its design of the UK 4G auction and submissions to competition bodies – under-estimated the long-term value of capacity spectrum for 4G. This has led it to be too relaxed about growing asymmetries in overall spectrum holdings, while at the same time adopting an auction format and applying restrictive bidding rules on 800 MHz spectrum that fundamentally disadvantaged O2 and Vodafone in the UK 4G auction. Vodafone was able to escape this problem by bidding far more than other bidders in the UK 4G auction, whereas budget-constrained O2 ended up with an inefficiently small package, despite (as we show here) having enough budget to buy more spectrum.

3.1. The evolution of asymmetry

Figure 2 maps the evolution of shares in usable spectrum across UK mobile operators since 2008. As can be seen, prior to the merger of Orange and T-Mobile that formed EE, shares in usable spectrum across the four largest MNOs were relatively even (20-24% each), although new entrant H3G (which had no 2G network) lagged behind (9%). The merger allowed EE to establish a large lead in usable spectrum, with a 39% share, compared to 23% for Vodafone and 20% for O2. At around the same time, the UK Government issued a Direction to Ofcom to convert existing 900 MHz and 1800 MHz licences to indefinite usage rights with liberalised use.[11] This made it possible for EE uniquely to launch 4G services in October 2012, ahead of the UK 4G auction, a 10-month lead on the other operators.[12]

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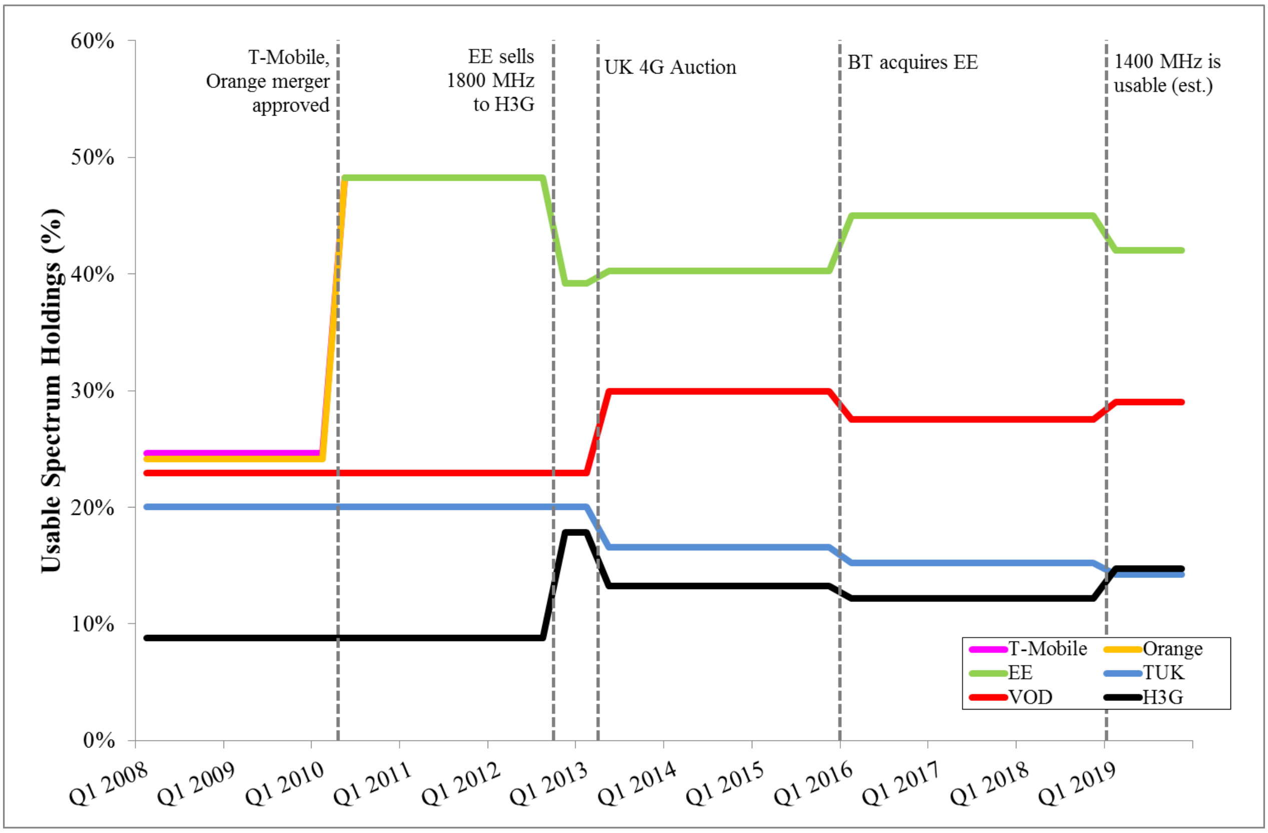
[10] In the UK, this means the following bands: 800 MHz FDD, 900 MHz FDD, 1800 MHz FDD, 2.1 GHz FDD, 2.6 GHz FDD and 2.6 GHz TDD. In addition, 2.3 GHz TDD also falls into this category but has not yet been released.

[11] Wireless Telegraphy Act 2006 (Directions to OFCOM) Order 2010.

[12] Vodafone and O2 launched their 4G networks in August 2013, followed by H3G in December 2013.

Figure 2: Evolution of shares of usable spectrum across UK mobile operators



Notes: Excludes holdings of usable spectrum by non-MNOs (e.g. BT from 2013-16). Values beyond 2017 show how spectrum shares would evolve through 2019 in the reference case where no MNOs acquired new spectrum
Source: NERA Economic Consulting, using public domain data.

When reviewing the merger, the EC and Office of Fair Trading expressed concern that it would result in there being only one operator that could offer full speed LTE using a 2x20 MHz carrier. The competition authorities feared that a bifurcation of the market could occur if other operators could not get access to sufficient spectrum to create a sufficiently large LTE carrier to delivery high speeds.[13] They ultimately accepted a remedy that involved EE selling 2x15MHz in the 1800 MHz band to another operator. One of the reasons given for the remedy being accepted was that 2.6 GHz would be released in the future which the competition bodies noted would allow other operators to create 2x20 MHz carriers to compete with the 1800 MHz LTE network of EE.[14]

The spectrum was ultimately sold to H3G shortly before the UK auction, meaning that H3G became one of only two operators, alongside EE, that was not dependent on winning spectrum in the auction to immediately launch 4G. Both O2 and Vodafone were possible buyers but both declined to bid, as Ofcom set up the rules for the 4G auction in a way that incentivised them to leave the spectrum for H3G. Had either O2 or Vodafone taken the

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[13] See §121 of Case No Comp/M.5650 - T-Mobile/ Orange - Regulation (EC) No 139/2004 Merger Procedure, European Commission (March 2010).

[14] Ibid, §127-128.

1800 MHz block, Ofcom would have defined the minimum package that was *de facto* reserved for H3G as 2x10 MHz at 800 MHz, instead of 2x5 MHz. Our understanding is that such a restriction was untenable for O2 and Vodafone, as they each needed 2x10 MHz at 800 MHz to deploy LTE on their existing 900 MHz grid and facilitate a network share arrangement. O2 tell us that they were not willing to take the risk of having more 800 MHz spectrum reserved for another bidder, given the likelihood that EE would be a very strong bidder for at least 2x5 MHz.

The 800 MHz and 2.6 GHz bands added 250 MHz of spectrum to the total available to MNOs, an increase of over 70%. As such, the auction had the potential to radically transform the relative holdings of the four remaining operators. In particular, the auction could have resulted in all four operators gaining access to sub-1 GHz spectrum for coverage and all four operators having access to at least one large block (ideally 2x20 MHz) at either 1800 MHz or 2.6 GHz for LTE. This was the outcome that most commentators expected. However, the actual outcome was very different. Instead of H3G, O2 and Vodafone gaining a stronger foothold in capacity spectrum, EE was able to extend its lead, securing an incredible 2x35 MHz in the 2.6 GHz band, with Vodafone and BT sharing the rest of the band. Below, we present evidence which we consider to be compelling that this auction outcome was grossly distorted by bids that did not reflect true relative valuations, a situation exacerbated by unintended side effects and strategic bidding made possible by the use of a combinatorial clock auction (CCA) format and complex competition rules.

Following the auction, EE's share of usable mobile spectrum rose to the maximum permitted 37%, ahead of Vodafone with 28%. H3G and O2 ended up with just 12.2% and 15.2% of usable spectrum respectively. H3G and O2's respective shares of paired spectrum (which at the time was considered much more valuable than unpaired) were just 13% and 16% respectively, either within or only just above the 10-15% threshold that Ofcom had concluded was the minimum necessary in order to act as a credible national wholesaler.[15] As illustrated in Figure 2, the auction enabled EE to consolidate the spectrum advantage it had established through the merger of Orange and T-Mobile.

In January 2016, the UK Competition and Markets Authority (CMA) approved BT's acquisition of EE. BT acquired EE without any remedies in relation to spectrum holdings, meaning that BT could aggregate its existing and newly acquired 2.6 GHz holdings, thereby lifting EE's share of currently usable spectrum to 45%. In effect, the CMA decision has allowed EE to circumvent the 37% precautionary cap imposed in the UK 4G auction, securing spectrum that would otherwise have gone to other MNOs. As illustrated in Figure 2, the spectrum share gap between EE and O2 is now even larger than in the period following the Orange-T-Mobile merger and before the remedy package of selling 2x15 MHz at 1800 MHz was implemented.

The CMA's decision was heavily influenced by Ofcom, which told them that:

> "*For any advantage that BT/EE would have in terms of additional spectrum capacity, we have set out above that in the longer term all MNOs will have a reasonable*

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[15] See §4.54 of Ofcom's "Assessment of future mobile competition and award of 800 MHz and 2.6 GHz", July 2012.

> *opportunity to increase capacity using a wide range of methods. While we have not assessed whether other MNOs may be capacity constrained in the short term, even if they were, this would not be so material as to threaten their long-term viability.*"[16]

We present evidence in Section 5 that Ofcom has overstated the ability of O2, in particular, to use non-spectrum measures to continue to expand its capacity. We also present evidence in Sections 5 and 6.3 that [✂] REDACTED. Regardless, the effect of the CMA decision has been to cut off one of the last remaining paths for O2 to expand its poor spectrum holdings, by acquiring unused spectrum from BT. It thereby puts the focus squarely on Ofcom to ensure that operators with poor spectrum positions have an opportunity to secure more spectrum in the PSSR award. Indeed, the CMA explicitly makes this point when it says that: "*there will be ample opportunity for any of the MNOs to obtain more [spectrum], if required, in the short to medium term.*"[17]

Shortly after BT announced plans to acquire EE, H3G reached an agreement to buy O2. The merger was rejected by the EU Authorities in May 2016, on grounds that it would unduly diminish competition in the retail market for mobile services and concern about the merged entity's ability to leverage its position of having network shares with both BT/EE and Vodafone. The decision was a victory, in particular, for Ofcom, which had forcefully argued in favour of preserving a four-player market structure.

Had the merger been approved, it would have created a market leader with a 46% subscriber share. The combined entity would have had 185 MHz of spectrum, 28% of the total currently in the market. While it would still have been underweight in spectrum relative to its subscriber share, it is reasonable to conclude that the merger would have addressed any medium-term concerns regarding the viability of O2's and H3G's capacity holdings, not least as the merged entity would have had two portfolios of sites nationwide. The decision to reject the merger eliminated another path for O2 and H3G to boost their capacity holdings, making the PSSR award even more important.

In July 2015, Qualcomm concluded the sale of its 40 MHz holdings in the L-band (1452-1492 MHz) in two chunks of 20 MHz, one each to Vodafone and H3G. The sale has no impact on holdings of currently usable spectrum, as 1400 MHz will not become available in handsets until later this year and then take several years to penetrate the user base. However, it has greatly improved H3G's medium-term capacity position and enabled Vodafone to reduce its spectrum deficit versus EE. Perhaps the most surprising feature of this sale is O2's failure to secure any spectrum, despite its parent company being an active bidder. We believe this can be attributed to the timing of the sale, which coincided with the merger [✂] REDACTED.[18] and Qualcomm's use of a quasi-first price sealed bid, which has poor efficiency properties.

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[16] See §3.47 of Ofcom's response on Anticipated acquisition by BT plc of EE Limited which was a Phase 2 submission to the CMA.

[17] See §66 of Appendix G to CMA's Report on the anticipated acquisition by BT Group plc of EE Limited (Jan 2016).

[18] [✂] REDACTED

3.2. The flawed assignment outcome of the UK 4G auction

The UK 4G auction should have been the event that supported an efficient rebalancing of spectrum across operators, reducing (but not eliminating) asymmetry in spectrum holdings, ahead of the anticipated huge rise in data traffic, and satisfying the concerns of the OFT and European Commission regarding access to 2x20 MHz LTE carriers. Instead, it exacerbated asymmetry, allowing one operator (EE) to establish an unassailable advantage in capacity spectrum, while leaving two operators (O2 and H3G) with spectrum holdings that are clearly inadequate to meet medium-to-long term growth in data demand.

This negative outcome occurred because the bids submitted in the auction were not reflective of the true relative valuations of the participants. The auction format that Ofcom selected for the 4G award, the CCA, uses a package bid approach which is guaranteed to identify the most efficient auction outcome *based on bids received*. However, the CCA only works as intended if the *bids reflect valuations*. Below, we present definitive evidence that bids did not adequately reflect valuations, and that the auction outcome would have been different if bids had more accurately reflected value. In particular, we show that an efficient outcome would have resulted in a reduction in spectrum asymmetry across the MNOs. We also explain how the apparent ‘failure’ of three of the four MNOs (EE, H3G and O2) to follow a straightforward valuation-based bid strategy can be attributed to risk and strategic incentives created by Ofcom’s choice of auction format and detailed rules.

The flawed outcome of the UK auction can be attributed to three factors:

1. O2 was subject to a **hard budget constraint** that, in the context of the CCA format, prevented it from expressing its full value for incremental spectrum in the 2.6 GHz band. In hindsight, we now know that O2 could have rearranged its bids within its budget to have comfortably won its target package of 2x10 MHz at 800 MHz and 2x20 MHz at 2.6 GHz. However, doing so would have meant exposing the company to the obviously unacceptable risk of winning nothing, and thus having no 4G option.

2. In both the clock and supplementary rounds, EE and H3G engaged in **bidding behaviour that appears strategic** and cannot obviously be explained by intrinsic valuations. In particular, they both adopted a tactic of bidding up the price of 800 MHz and then dropping out of bidding for once they were certain this would result in the clock rounds ending with unsold lots (EE later did the same for 2.6 GHz paired). This approach created maximum uncertainty for other bidders, which in turn precipitated O2’s budget problem and led EE to win ‘too much’ spectrum.

3. BT acquired spectrum based on a **business case that it ultimately did not pursue**. This spectrum is still unused but has been merged into EE’s holdings, enabling EE to bypass the 37% cap on holdings imposed in the UK 4G auction.

We explain each of these factors below. By far the most important is the budget constraint on O2.

3.2.1. O2's hard budget constraint

In a previous submission to Ofcom, NERA presented evidence that O2 subject to a hard budget constraint in the UK auction, and this was a key reason why the auction failed to deliver an efficient outcome. Specifically, the budget constraint prevented O2 from submitting bids that would have enabled it to secure 2x20 MHz at 2.6 GHz, in addition to the 2x10 MHz at 800 MHz that it won. In response, Ofcom made the point that procuring sufficient budget was the responsibility of a bidder, the implication being that it was not Ofcom's responsibility to save bidders from their own mistakes. As a general principle, we agree with Ofcom's point but we strongly disagree that it is relevant to this case.

The key issue here is that O2 did, in fact, procure sufficient budget (£ [✂] REDACTED)to secure its target package. O2's failure to win the target package was a direct result of Ofcom's CCA format, which left O2 unduly exposed to the risk of winning nothing. In effect, the bidding process obliged O2 to [✂] REDACTED on ensuring it won essential spectrum at 800 MHz, leaving it unable to express sufficient incremental value for 2.6 GHz. Had an alternative auction format been used, such as the SMRA variant proposed for the PSSR award, O2 would have won its target package, as (assuming unchanged bid preferences from rivals) prices would <u>not</u> have climbed to the point that O2's budget constraint became relevant.

To demonstrate the impact of O2's budget constraints, we re-ran the winner determination programme (WDP) for the 4G auction, but with O2's bids for packages with between two and eight incremental 2.6 GHz lots (in addition to 2x10 MHz at 800 MHz) included at valuation. None of these bids would have violated O2's supplementary round bid constraints created by its clock round bids.[19]

The results are illustrated in Table 1, with the changes versus the actual auction outcome shown in parentheses. The impact on assignment is dramatic. O2 secures its target package of 2x10 MHz at 800 MHz and 2x20 MHz at 2.6 GHz. Instead of winning 1 lot at 800 MHz and 7 lots of 2.6 GHz paired spectrum, EE picks up a package of 2 lots at 800 MHz and 9 lots of 2.6 GHz unpaired. H3G is flipped from winning 1 lot at 800 MHz to 4 lots at 2.6 GHz paired. BT acquires significantly less spectrum. Overall, the outcome is a close fit with O2's pre-auction valuation forecasts, and – unlike the actual auction outcome – this distribution of spectrum across the bidders makes reasonable sense from an intrinsic value perspective. Observe also that the price for O2's larger winning package is almost £ [✂] REDACTED below its budget constraint.

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[19] For a full explanation of our methodology, including relevant valuations, we refer Ofcom to NERA, September 2016, Section 1.3.1.

Table 1: Alternative outcome of UK 4G auction if O2 had expressed full incremental values for 2.6 GHz spectrum

	800 MHz (# lots)		**2.6 GHz (# lots)**		**Bid amount**	**Base price (£000s)**
	2x5	**2x10**	**2x5**	**5**		
BT	0	0	**2 (↓1)**	**0 (↓4)**	£245,431	[✂] REDACTED
EE	**2 (↑1)**	0	**0 (↓7)**	**9 (↑9)**	£1,090,500	[✂] REDACTED
H3G	**0 (↓1)**	0	**4 (↑4)**	0	£400,500	[✂] REDACTED
O2	0	1	**4 (↑4)**	0	£1,701,000	[✂] REDACTED
VOD	2	0	4	**0 (↓5)**	£1,990,000	[✂] REDACTED

Source: NERA Economic Consulting using data from Ofcom and O2
Notes: Shows number of lots and base price for alternative outcome (change from actual auction outcome is shown in parentheses)

Such an outcome would have reduced spectrum asymmetry and provided both O2 and H3G with viable capacity portfolios beyond the short term. Assuming no change to other spectrum events, the current usable spectrum holdings across the MNOs would have changed as follows[20]:

1. O2's total holdings would now be 126.4 MHz, up from 86.4 MHz, and 22.1% instead of 15.2% of the total;

2. H3G's total holdings would now be 99.2 MHz, up from 69.2 MHz, and 17.4% instead of 12.2% of the total;

3. EE's total holdings would now be 210 MHz, down from 255 MHz, and 36.7% instead of 45.0% of the total; and

4. Vodafone's total holdings would now be 136 MHz, down from 156 MHz, and 23.8% instead of 27.5% of the total.

In hindsight, we can see that O2 would have been better off following Vodafone's strategy of bidding its way out of trouble. However, this would have required O2 to submit a bid of over £1.7bn for spectrum with a market price below £900m. There is something deeply flawed

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[20] We exclude 1400 MHz from these calculations, as it is not yet usable. We assume that 40 MHz of 2.6 GHz TDD is usable for EE.

about an auction format that requires a bidder to express a bid amount so hugely in excess of market price in order to secure an efficient outcome. Ofcom implicitly recognises this point when it says at CD §2.23 that auctions should be designed such that "*bidders should not feel that they would have bid differently when they see the final result*." Clearly the outcome of the UK 4G auction did not meet this objective.

In making these observation, we are not seeking to dispute the results of the 4G auction. They were run under rules developed through consultation and accepted by all bidders. Nevertheless, we think it is beholden to Ofcom to recognise that, in this case, its auction format almost certainly delivered the wrong outcome. The PSSR award offers an opportunity for Ofcom to guide the market back in the right direction.

3.2.2. Strategic bidding behaviour

Auctions work best when bidders bid straightforwardly based on their valuations. A key reason that Ofcom adopted the CCA for the UK 4G auction was the hope that this new format would encourage valuation-based bidding. Unfortunately, the weight of evidence suggests that this was not the case.

In our previous submission to Ofcom, we highlighted two areas of concern that we believe contributed to the failure of the auction to deliver an efficient auction outcome:

1. There is evidence that both EE and H3G engaged in price driving tactics during the clock rounds, which successively inflated the prices of lots in the 800 MHz, paired 2.6 GHz and unpaired 2.6 GHz bands. This in turn subverted the price discovery mechanism, and created a situation where O2 was obliged to exhaust its large budget on the 800 MHz band, when it otherwise could have also secured 2.6 GHz spectrum. This tactic was facilitated by Ofcom's eligibility point rule which prevented switching back and fore between the bands.

2. The bid profile of EE is odd. Its expressed bids for larger quantities of 2.6 GHz paired spectrum are exceptional outliers to O2's pre-auction estimates of value for other bidders[21] (which otherwise appear fairly accurate), and very different from Vodafone's revealed valuation structure. It is possible that EE overbid for 2.6 GHz paired spectrum relative to rivals for tactical reasons, perhaps because it was trying to drive prices for rivals or because it anticipated strategic investment benefits from outcomes that blocked rivals.

Absent full disclosure from all participants, it may be impossible to conclude definitively that the auction outcome was distorted by strategic behaviour and inappropriate valuations. Nevertheless, we consider that the circumstantial evidence that such behaviour contributed to the inefficiency in the auction outcome is compelling. In particular, it is clear that the behaviour of EE and H3G in driving prices then dropping demand (leading to unallocated lots at the end of the clock round) precipitated the uncertainty over the auction outcome that made O2's budget constraints relevant. Whether one attributes this to strategic bidding or the

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[21] [✂] REDACTED.

constraints created by Ofcom’s eligibility points rule, it is clear that price discovery was subverted.

In hindsight, we think that Ofcom severely underestimated the scope for strategic behaviour in the auction, and the extent to which the format disadvantaged O2 and Vodafone. Going into the auction, EE and H3G already had sufficient spectrum to launch 4G services at frequencies compatible with their 1800/2100 MHz-based networks, and had formed a network share arrangement to exploit this. Telefonica and Vodafone did not have this security. This made them exceptionally dependent on winning 800 MHz, given the synergies between acquiring this and their 900 MHz-based networks. Ofcom was clearly aware of this: in its competition assessment prior to the auction, it recognised that Telefonica needed to secure at least 2x10 MHz additional spectrum “*to be credible*.”[22] However, it presumably concluded that O2 and Vodafone were strong enough to look after themselves. Under a different format, this might have been true, but it was not so in the context of a CCA format that could bust even large budgets through illusionary price driving.

An important parallel between the UK 4G auction and the PSSR award is the expectation from competition authorities in a prior merger assessment that primary awards can address any concerns regarding access to large blocks of 4G capacity spectrum. In 2013, the auction failed to meet this expectation, in large part because the auction format did not provide a level playing field for bidders. Under its current proposals, we see a risk that Ofcom could fall into the same trap. There is again an obvious asymmetry between the bidders, with O2 and H3G requiring more spectrum for 4G capacity than EE and Vodafone. In proposing minimally interventionist remedies, Ofcom again appears to be relying on the assumption that higher intrinsic values will win out, even though recent history should give it no such confidence.

3.2.3. BT’s business case for 2.6 GHz spectrum was never implemented

BT was a key player in the UK 4G auction, bidding for substantial quantities of 2.6 GHz spectrum, and winning 2x15 MHz paired and 25 MHz unpaired (of which 15 MHz was available for high power use). As EE won spectrum at its cap, BT’s participation had the effect of reducing spectrum for the other three MNOs. This was not a concern at the time, as it was assumed that BT’s bids were based on a viable business case. However, BT never deployed the spectrum that it won. Instead, it has now purchased EE, and merged their spectrum resources together. In effect, BT’s acquisition of EE circumvented the prudential spectrum caps that Ofcom introduced for the 4G auction.

In hindsight, given BT’s failure to deploy the spectrum and its “*limited expectations of its femtocell strategy over the next few years*”[23], it seems that its business case was unviable. Most likely, its value was always inflated by strategic considerations regarding a future tie up with a mobile operator. Indeed, O2 tell us that BT released an ITT for wholesale mobile access in March 2013, immediately after the auction, that included an exploratory offer to

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[22] See §4.131 and 4.132 of Ofcom Assessment of Future Mobile Competition and Award of 800 MHz and 2.6 MHz, July 2012.

[23] CMA’s Report on the anticipated acquisition by BT Group plc of EE Limited, Jan 2016, §11.47.

share 4G spectrum assets. Regardless, the issue here is that BT was allowed to merge its spectrum into EE’s holdings, where they still lie unused some four years after the auction. It is hard to conceive that this represents an efficient use of spectrum, when other operators face severe capacity constraints.

To illustrate the impact of BT’s participation on the other MNOs, we re-ran the winner determination excluding BT’s bids. As shown in Table 2, O2 would have secured 2x10 MHz at 2.6 GHz, with the remainder of BT’s spectrum going to Vodafone. This may understate the impact of BT’s participation, as their bidding activity may also have been a contributory factor in the excessive pricing of 2.6 GHz in the clock phase, which in turn was the cause of O2’s budget issues in the supplementary round.

Table 2: Alternative outcome of UK 4G auction if BT’s bids are excluded

	800 MHz (# lots)		**2.6 GHz (# lots)**		**Bid amount**	**Base price** (£000s)
	2x5	**2x10**	**2x5**	**5**		
BT	-	-	**- (↓3)**	**- (↓4)**	NA	NA
EE	1	0	7	0	£1,049,500	£517,888 (↓70,988)
H3G	1	0	0	0	£565,500	£225,000
O2	0	1	**2 (↑2)**	0	£1,347,003	£658,200 (↑£108,200)
VOD	2	0	**5 (↑1)**	**9 (↑4)**	£2,133,520	£761,769 (↓£41,091)

Source: NERA Economic Consulting using data from Ofcom
Notes: Shows number of lots and base price for alternative outcome (change from actual auction outcome is shown in parentheses)

The CMA allowed BT’s acquisition of EE to proceed without any spectrum remedies. However, its remit was only to consider whether allowing the merged entity to retain all of its spectrum would have anti-competitive effects, not whether this was an efficient assignment of spectrum. For it to be efficient, you would have to believe that EE places a higher intrinsic value on the spectrum than O2, despite having similar market share and more than twice as much spectrum. In contrast, for it to be acceptable from a competition perspective, the CMA only had to conclude, as it did, that any associated competition concerns could be remedied through future spectrum awards, in particular the PSSR award. We return to this issue in Section 6.

4. Spectrum asymmetry in the UK is exceptional when compared to other countries worldwide

When compared to other countries, the extent of spectrum asymmetry across UK mobile operators is exceptional. The UK is the only country in Europe to have two operators with spectrum share of 15% or less.[24] The spectrum positions of BT and O2 are also particularly unusual. Despite operating in a four-player market, BT has the largest holdings of usable spectrum in Europe, ahead of even the largest operators in three-player markets. In contrast, O2 has one of the lowest spectrum shares amongst European operators, and its ratio of spectrum share to subscriber share ranks last across our sample of 320 operators in 100 countries.

In this section, we present a series of international comparisons to demonstrate just how unusual the UK spectrum allocation is. Our analysis is in three parts:

- In Section 4.1, we compare spectrum holdings of UK operators with their European and international peers, based on four different metrics. Together, they reveal a picture of the unusual extent of spectrum asymmetry in the UK market.
- In Section 4.2, we compare Ofcom's policy on spectrum caps to other countries, and show that Ofcom is amongst the least interventionist of European regulators, despite a starting point of much greater asymmetry.
- In Section 4.3, we profile other European operators with spectrum shares at or below 15%. In all cases, these are relatively recent market entrants that have benefited from substantial regulatory support; several of them are struggling. We conclude that there is no evidence from other European markets to support Ofcom's assertion that a spectrum share of 10-15% is sufficient to support credible competition in the long term.

We believe that this evidence should be a red flag to Ofcom that extreme spectrum asymmetry, if allowed to persist, could have damaging repercussions for consumers and the economy at large. Put differently, if Ofcom persists with policies that allow for a subset of operators to maintain or even grow their very large market shares, it should present a much stronger rationale why it is willing to take such a different approach from other regulators worldwide.

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[24] Slovenia had two operators, Telemach and T-2, under the threshold at the time that the Consultation was drafted. However, Telemach acquired purchased 2x5 MHz of 2100 MHz in December 2016. After this transaction, Telemach owns 16% of usable spectrum held by MNOs in Slovenia.

4.1. Global Assessment of spectrum holdings

To demonstrate the current extent of asymmetry in spectrum holdings in the UK, we consider four different metrics:

1. total spectrum holdings by operator;
2. access of operators to larger blocks of spectrum suitable for LTE;
3. a measure of spectrum concentration for four-player markets; and
4. the ratio of spectrum share to subscriber share by operator.

For the first three metrics, we compare UK operators with their European peers, which we consider the most relevant sample given most European countries have released comparable amounts of spectrum in similar bands into the market. For the final metric, we extend our sample to 320 operators across 100 markets worldwide, i.e. every country where we could obtain data on spectrum holdings and subscriber share.

4.1.1. Total holdings of usable spectrum

Each operator's total spectrum holdings provide a good indication of their ability to expand network capacity, both to accommodate growth in demand for 4G data and potentially expand market share. NERA maintains a database of total spectrum holdings of mobile operators in countries worldwide. For this metric, we have identified 90 MNOs across 27 European countries. We limit our sample to European countries[25] (as all use comparable spectrum bands) and operators with market share greater than 4% (as operators with holdings smaller than this are typically not credible mass market players). We only consider holdings of currently usable spectrum.[26]

The results are shown in Figure 3. On this metric, two UK operators languish in the bottom ten in total spectrum holdings: O2 ranks 85th and H3G ranks 87th. In contrast, BT ranks 2nd, ahead of operators in all three- and four-player markets except Telia in Estonia. It is even ahead of all German operators, despite Germany being a three-player market that has released more usable spectrum than the UK.

There are four operators that rank below O2 and/or H3G in total spectrum holdings. We do not consider any of them to be good comparators for UK operators:

- Romania – RCS (8.5% market share, launched in 2007) – declined option to buy unsold spectrum in 2012 4G auction.
- Spain – Yoigo (5.8% market share, launched in 2006) – declined to participate in 4G auction and declined option to buy reserved spectrum.

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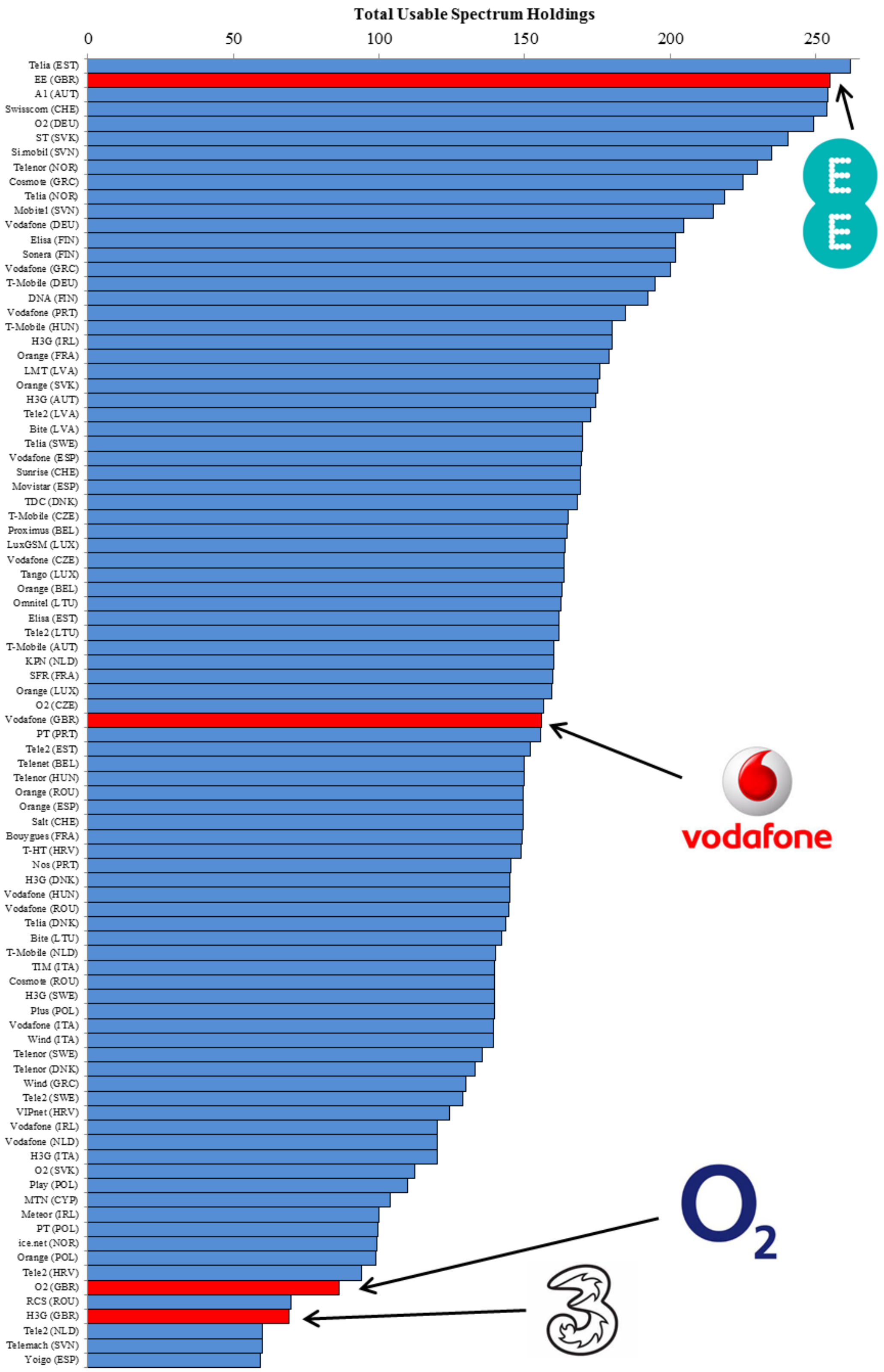
[25] EU member states plus Switzerland and Norway. We exclude Bulgaria, Cyprus and Malta because their allocation of spectrum lags far behind other European countries: as of January 2017, these three countries have not allocated any spectrum in the 800 MHz and 2600 MHz bands.

[26] Paired bands at 700, 800, 900, 1800, 2100 and 2600 MHz, and TDD bands at 2300 and 2600 MHz.

- Netherlands – Tele2 (4.9% market share, launched in 2015) – very recent entrant that has benefitted from reserved spectrum.
- Slovenia – Telemach (16% market share, launched in 2007) – has option to acquire more spectrum in future, which would lift its holdings above O2 and H3G.

The lowly position of H3G and O2 cannot be attributed to any failure on the part of Ofcom to release spectrum in the UK market. The UK ranks 10th out of 28 countries in terms of total spectrum released, and would rise to 4th if the available 40 MHz at 2.3 GHz band is released before other countries release any more spectrum.

Figure 3: Total usable spectrum holdings by European operator



Source: NERA Economic Consulting

4.1.2. Access to large blocks for LTE carrier aggregation

As highlighted by Ofcom in the Consultation, access to larger blocks of spectrum (i.e. 2x10 MHz up to 2x20 MHz) is important both as a way to cost effectively add 4G capacity and to increase peak data speeds using carrier aggregation (CD §A8.51). For our second metric, we consider the maximum number of large blocks potentially available to each operator in our sample of 90 European MNOs. In practice, the actual number of blocks deployed for LTE will lag behind this maximum, owing to legacy 2G and 3G use. As this analysis is forward looking, we include the 1400 MHz band (awarded in Germany and the UK), which should be usable by 2019, as well as currently usable bands. We do not include 3.4 GHz, as this has not been widely released and we do not have reliable data yet on its allocation across European operators.

In Figure 4, we present a comparison of the number of 20 MHz carriers (FDD downlink or TDD) available to each European operator. We exclude uplink blocks, as downlink capacity and speed is the most important concern from a competition perspective. In Figure 5, we perform the same analysis for 10 MHz blocks (in this case, we count 20 MHz as equivalent to two 10 MHz blocks, but only count 15 MHz as equivalent to 10 MHz). We are deliberately not counting isolated or residual 5 MHz blocks, as they offer a much smaller incremental benefit and are less likely to be used for carrier aggregation.

The comparison reveals a significant asymmetry both between UK operators, and between O2, H3G and their international peers:

- EE already has access to five 2x20 MHz carriers across the 1800, 2100 and 2600 MHz bands, the joint highest level of any operator in Europe.

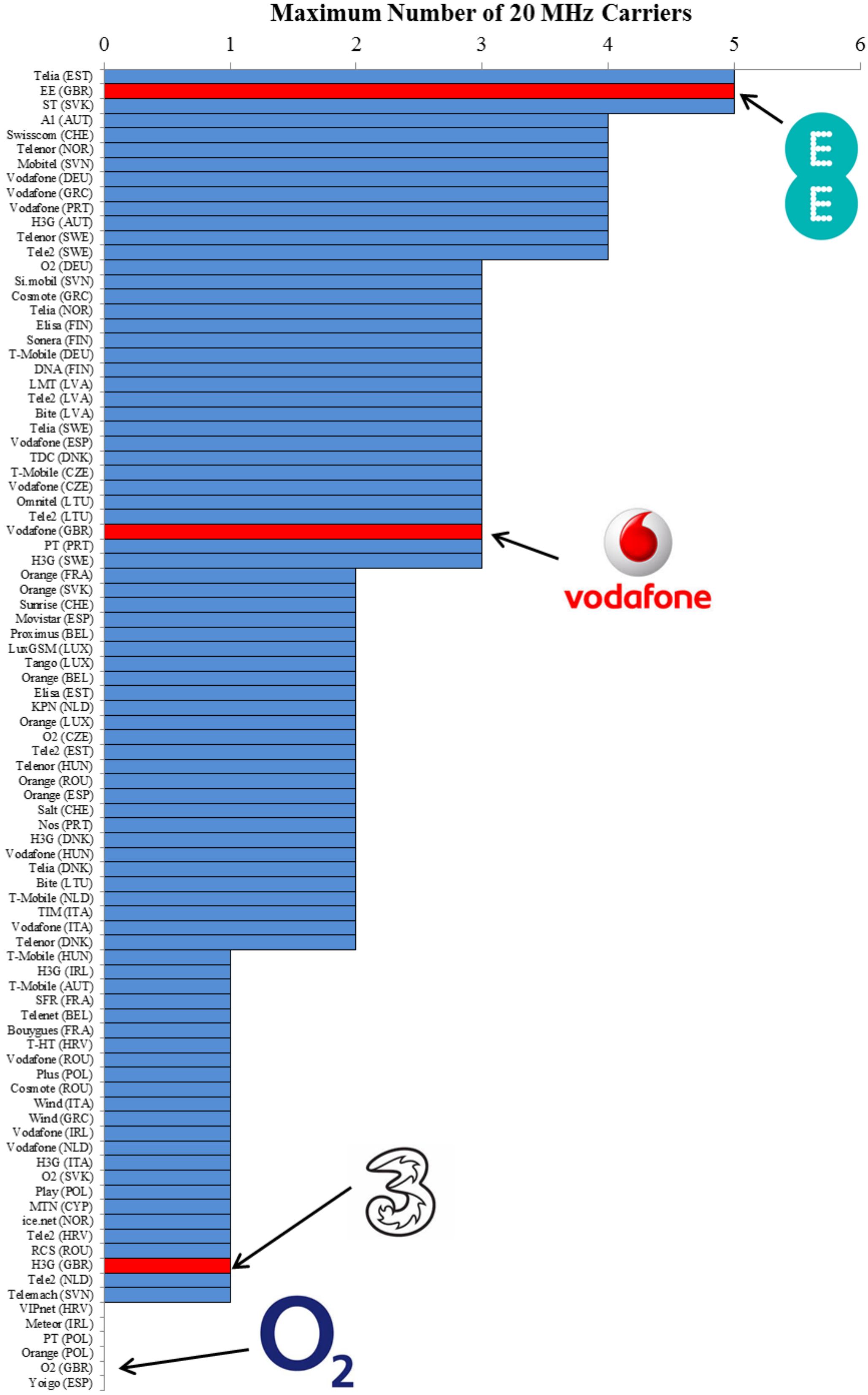
- Vodafone is also well positioned with access to three 20 MHz blocks (one 2x20 FDD and two 20 MHz TDD / SDL blocks, although its 1400 MHz block will not be usable until 2019). This places it above the European average.

- H3G UK lags well behind. It has only one 20 MHz blocks at 1400 MHz, which will not be usable until 2019. However, it does also have two 2x15 MHz blocks at 2100 MHz and 1800 MHz. Overall, its potential to access large LTE carriers is near the bottom of European operators.

- O2 UK sits at the very bottom, with the joint lowest access to large blocks of LTE spectrum amongst European operators. It is one of only six operators in our sample without access to a single block of 20 MHz. It does have access to two contiguous blocks of 10 MHz (at 800 and 2100 MHz), but this still places it at the bottom of the European league. O2 also has 2x17.5 MHz at 900 MHz, but this will only become usable for larger blocks of LTE if and when an agreement is reached with Vodafone to reconfigure the band and end current fragmentation of holdings.

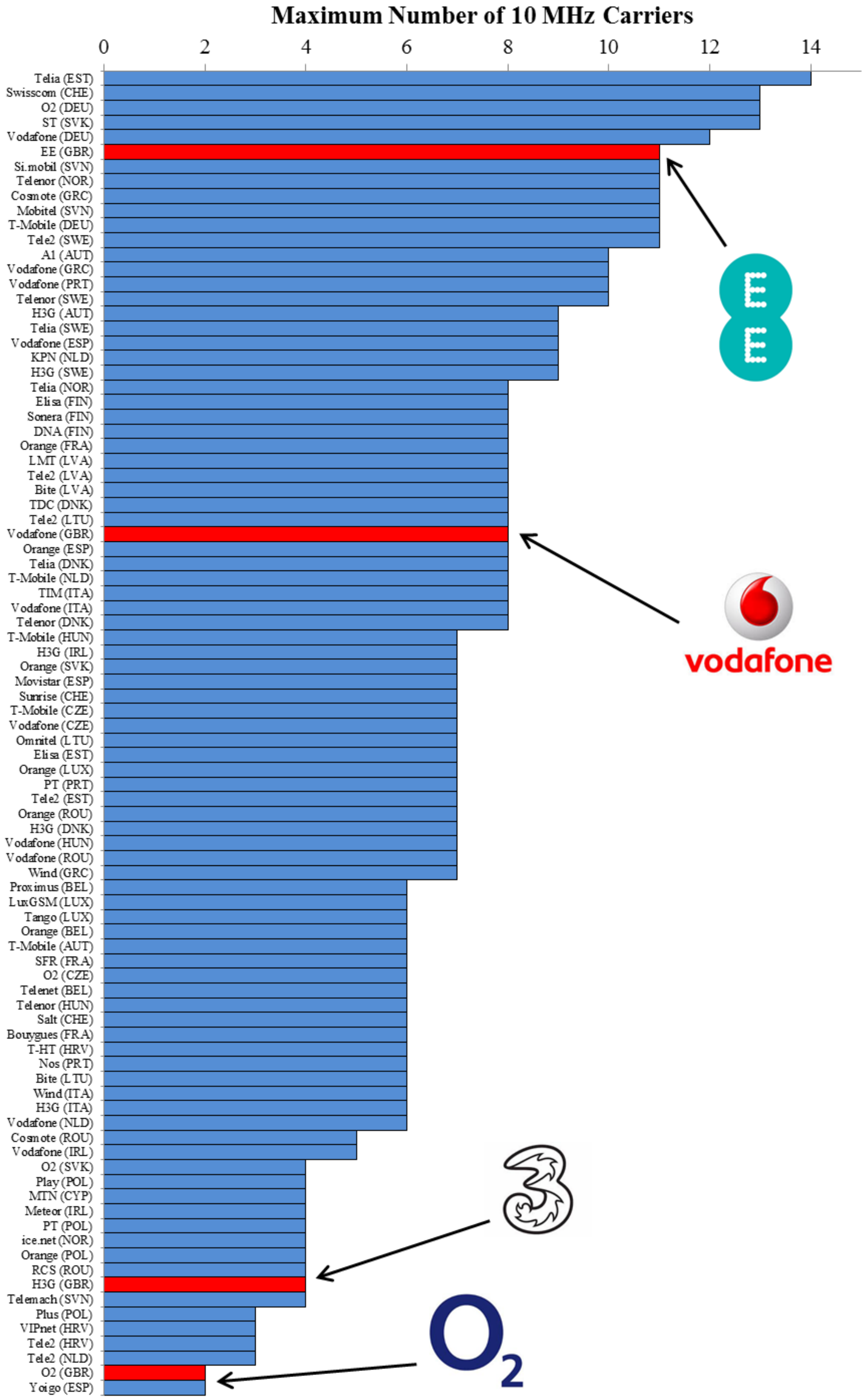
This discrepancy should raise serious concerns about the ability of O2, in particular, to remain a credible competitor in provision of 4G services unless it at acquires significant additional spectrum in the PSSR and subsequent awards.

Figure 4: Maximum number of 20 MHz FDD downlink or TDD carriers by operator



Source: NERA Economic Consulting

Figure 5: Maximum number of 10 MHz FDD downlink or TDD carriers by operator



Source: NERA Economic Consulting

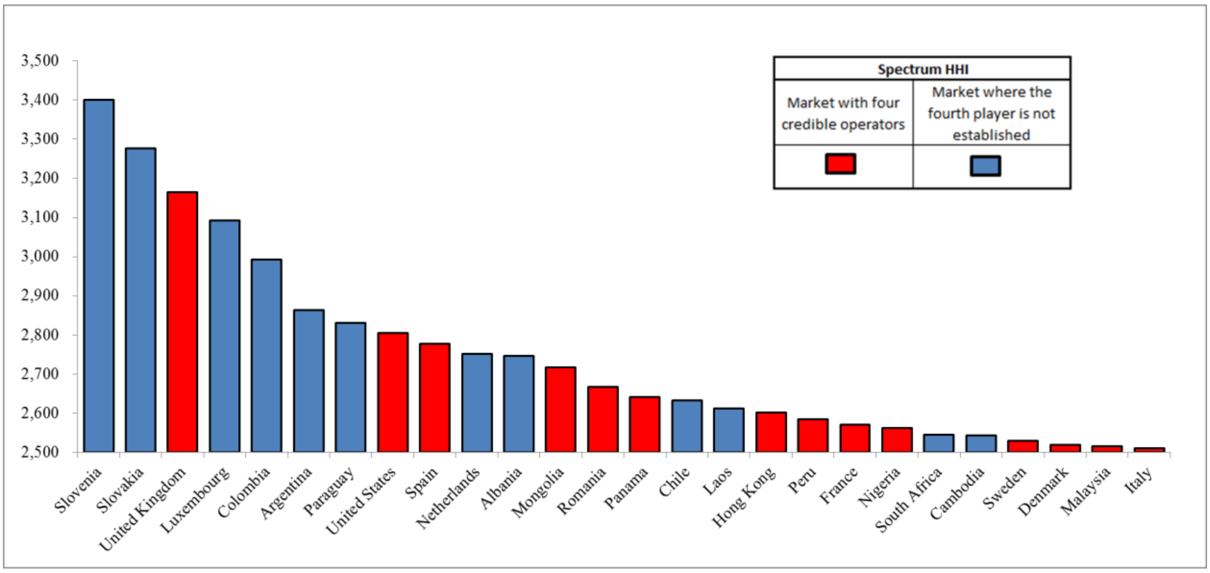
4.1.3. Spectrum share concentration ratio

The Herfindahl-Hirschman index (HHI) is a commonly accepted measure of market concentration. It is typically used in competition analysis, for example by the European Commission or US Department of Justice in merger analysis. It is calculated by squaring the market share of each firm competing in a market, and then summing the resulting numbers, and can range from close to zero to 10,000. A low HHI is considered an indication of a competitive market, while a higher HHI may indicate potential competition concerns.

Here, we use the HHI to compare the level of concentration in spectrum holdings across mobile operators. Across a sample of 100 countries worldwide, we identified a total of 26 markets with four players, including the UK. The lower bound for the HHI in a four-player market is $4 \times 25^2 = 2{,}500$, in the case that all spectrum is equally split between four competitors. We do not attempt to compare HHI levels to those in three-player markets, as the base level is $3 \times 33^2 = 3{,}267$ (an HHI at this level for a four-player market would indicate extremely asymmetric holdings).

In Figure 6, we compare HHI levels for spectrum holdings across these 26 countries.[27] The UK is 3,165, which is the third-highest HHI in the sample and significantly above the median of 2,654.

Figure 6: Concentration of spectrum holdings across four-player markets, using HHI



Source: NERA Economic Consulting

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[27] We define an MNO as an operator with at least 0.1% market share. MVNO subscribers are included in the MNO subscriber base that hosts the network. Data is from Telegeography Global Comms Database.

We also differentiate in Figure 6 between credible four-player markets (shown in red), which we define as those with four operators each with a market share of 5% of more, and other markets (shown in blue), where the fourth largest player is not established (market share below 5%). The only two countries that have higher HHI than the UK are countries where the fourth player is not established: Slovenia (where the fourth largest operator in bankrupt and has a 3.7% market share); and Slovakia (where the fourth largest operator Swan only recently launched and has a 2.5% market share). The next three markets below the UK also fail to meet our standard for credibility: Luxembourg (where fourth player LOL has a 1.5% market share); Colombia (Aventel, 1.6%); and Argentina (Nextel, 1.4%). Amongst credible four-player markets, the next highest spectrum HHIs after the UK are found in Paraguay at 2,831 points (where Hola has an 8.0% market share and 10.1% spectrum share) and the United States (where T-Mobile has a 18.1% market share and 14.1% spectrum share).[28] We note that T-Mobile is a bidder in the US 600 MHz auction, where it is the only participating national operator with nationwide eligibility for set-aside spectrum.

In the Consultation, Ofcom performed a similar analysis of spectrum HHIs but over a more limited sample. It highlighted Slovenia as an example of another country with four players and a high HHI. However, given that the fourth player is bankrupt and may exit the market, Slovenia cannot be considered as a credible four-player market. Amongst credible four-player markets, there is no country other than the UK with a spectrum HHI above 2,900 points.

Comparing spectrum shares is obviously not the same thing as comparing subscriber market shares, so a high HHI does not by itself necessarily indicate cause for alarm. Indeed, in the UK, there is currently no correlation between spectrum shares and market shares. Nevertheless, in Section 5, we present evidence that, over the coming years, access to spectrum is likely to become much more important as a binding constraint on the ability of operators to expand capacity. If our analysis is correct, this means that a high HHI for spectrum may be a forward indicator of future competition concerns in the downstream market. Accordingly, we think it would be prudent for Ofcom to consider adopting a target maximum acceptable level of HHI for spectrum holdings, and adopt spectrum caps that should guide the market in this direction. Based on international comparisons, this level should not exceed 2,900 points, a level that loosely corresponds to a 35% global spectrum cap.

4.1.4. Ratio of subscriber share to spectrum share

The ratio of subscriber share to spectrum share is a potentially good indicator of the ability of a company to grow its customer base. A company with a high ratio is likely to have significant excess capacity and be able to compete vigorously for customers and accommodate substantial growth in data demand. Conversely, a company with a low ratio may be capacity constrained: as data demand grows, it may be vulnerable to exhausting technical options to expand capacity, implying that existing customers will suffer deteriorating data rates and the company’s ability to compete for new customers will be constrained.

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[28] Telegeography Global Comms Database.

In the Consultation, Ofcom presents an analysis of subscriber share to spectrum share for a limited sample of countries. We have expanded this to 320 operators across 100 countries around the world. Spectrum shares are calculated based only on bands that are currently useable (i.e. excluding 1400 MHz). An operator with a ratio greater than 1 may be described as “overweight” in spectrum (more room to use spectrum to expand capacity), while an operator with a ratio below 1 may be described as “underweight” in spectrum (less room to use spectrum to expand capacity).

The results are shown in Figure 7. They reveal that O2 faces an exceptionally challenging position:

- **O2 ranks last of all 320 MNOs** in the sample with a ratio of just 0.44, reflecting its unique combination of strong market share but very low spectrum share. It is quite common for legacy 2G operators, such as O2, to be underweight in spectrum relative to subscribers. However, in other cases, this is invariably because they have very large market shares (e.g. KPN or TDC), not because the companies have low spectrum shares. Amongst European operators that launched before the 3G era, O2 is alone in having a spectrum share below 20%.

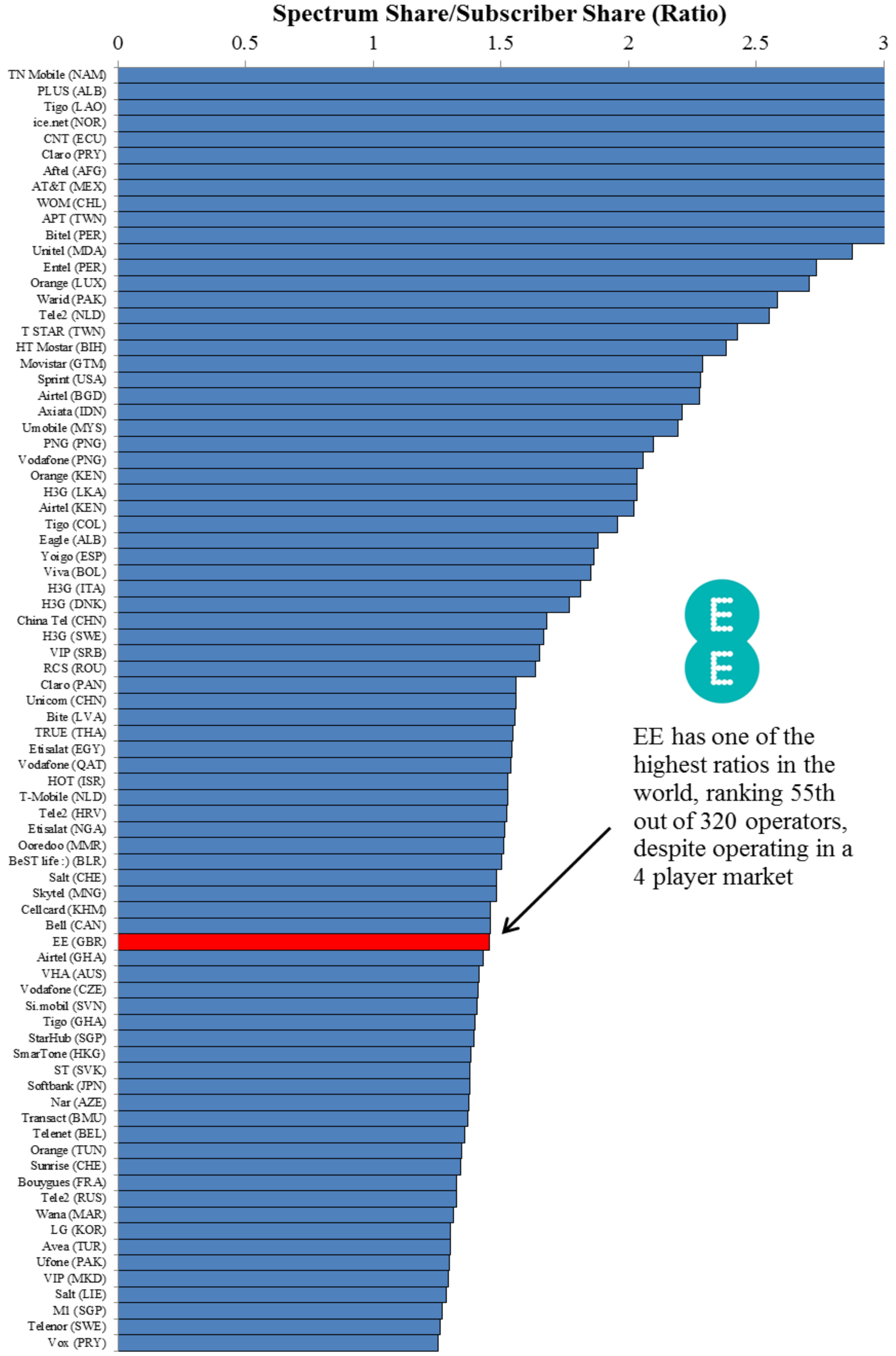
- **EE is heavily overweight in spectrum** notwithstanding its strong subscriber share. It ranks 55th of a total of 320 MNOs with a ratio of 1.46. Furthermore, there is only one MNO with a subscriber share that is equal to or higher than EE that has a larger ratio (Vodafone Qatar).

- **Vodafone is also relatively overweight in spectrum** with a ratio of 1.22, ranking 83rd of a total of 320 MNOs.

- **H3G UK’s position is close to the median**, ranking 146th of 320 with a ratio of 1.02; as its low spectrum share is balanced by a modest subscriber share. However, this metric understates H3G’s need for additional capacity, as its customer base is exceptionally skewed towards heavy data users.

As we discuss in Sections 5, [✂] REDACTED. We address the implications of this for efficiency and competition in Section 6.

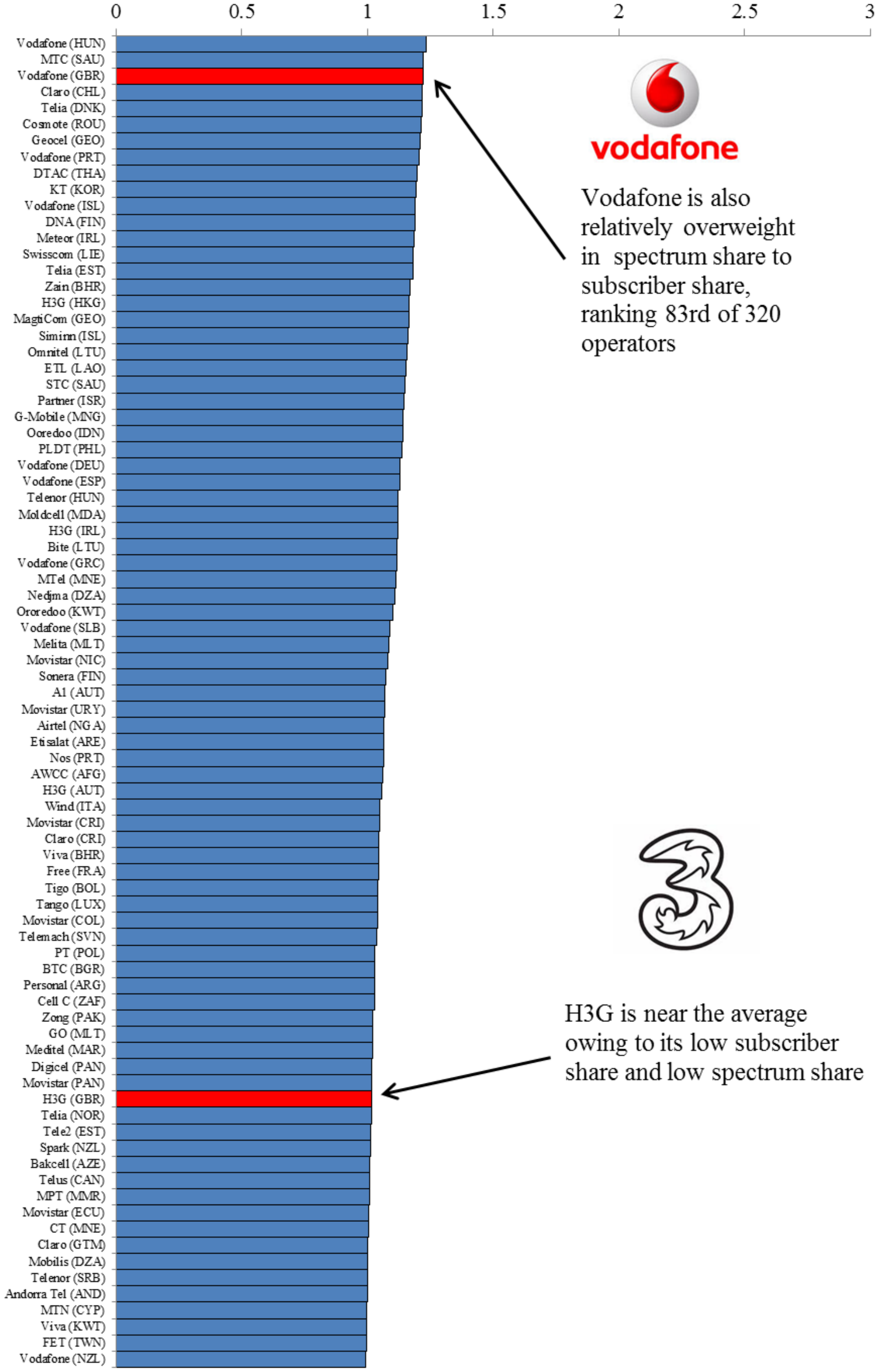
Figure 7: Ratio of subscriber share to spectrum share for 320 operators worldwide



EE has one of the highest ratios in the world, ranking 55th out of 320 operators, despite operating in a 4 player market

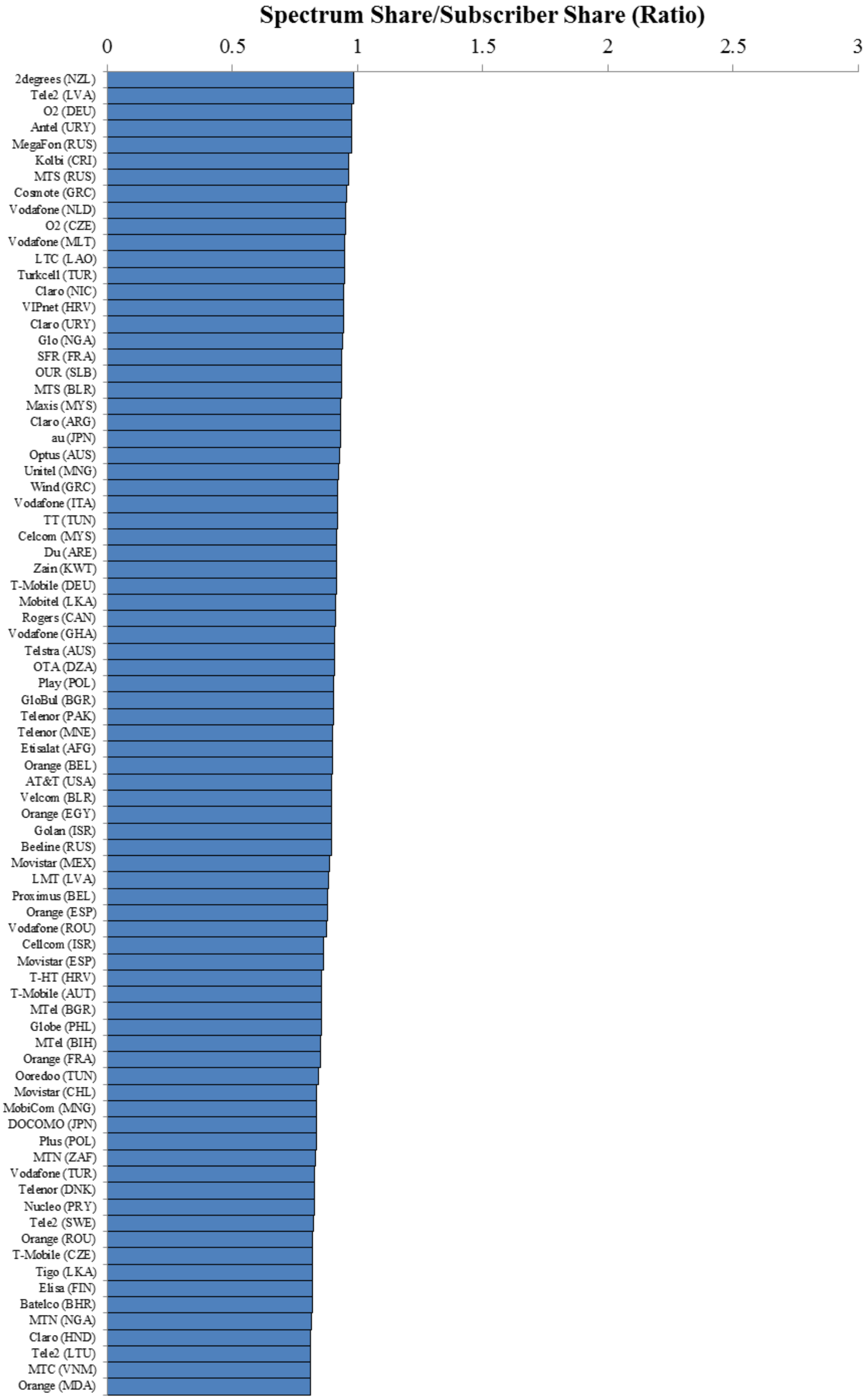
Note: The graph truncates ratios above 3.0.

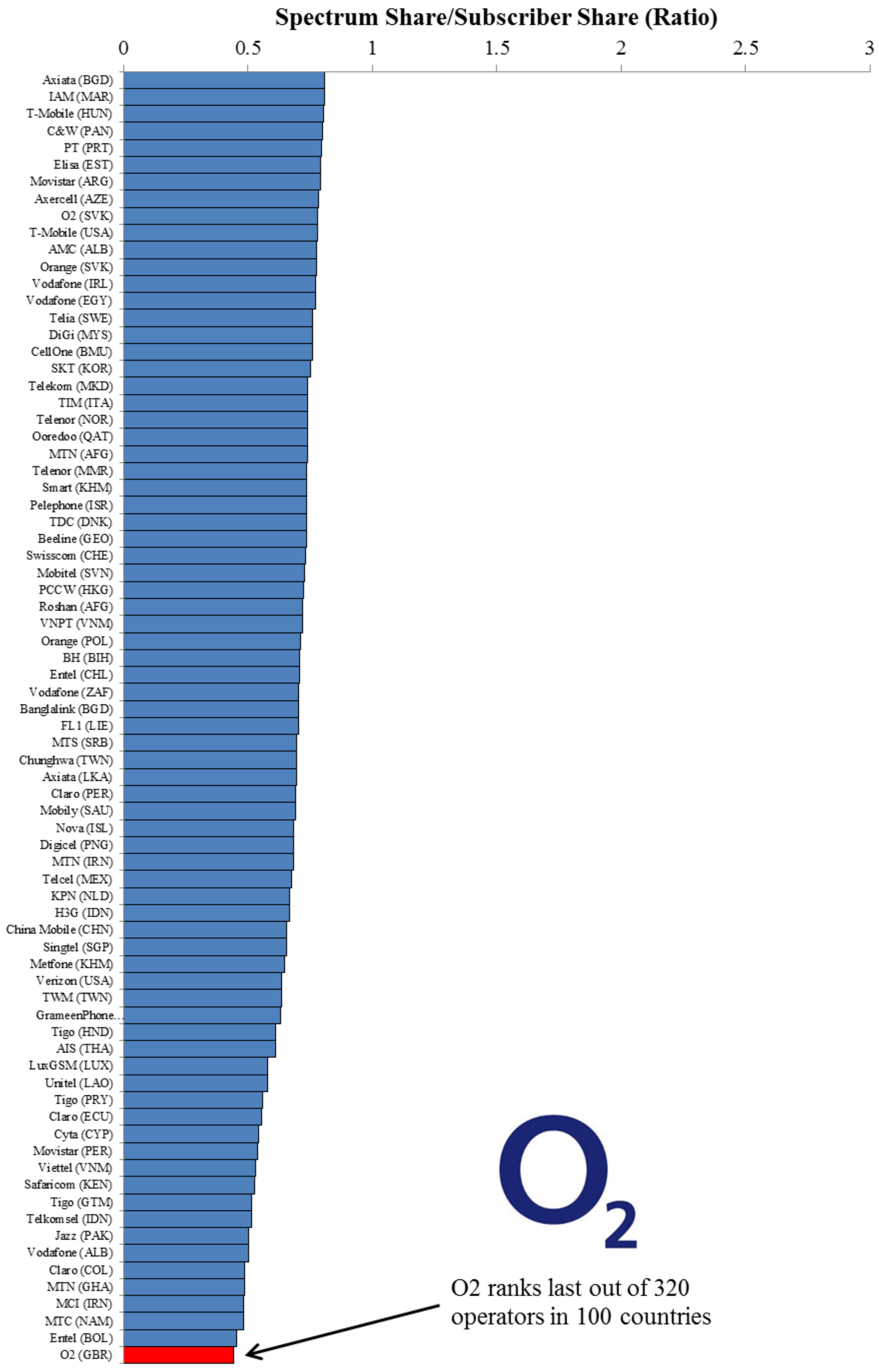
Spectrum Share/Subscriber Share (Ratio)



Vodafone is also relatively overweight in spectrum share to subscriber share, ranking 83rd of 320 operators

H3G is near the average owing to its low subscriber share and low spectrum share


Spectrum Share/Subscriber Share (Ratio)
0
0.5
1
1.5
2
2.5
3
2degrees (NZL)
Tele2 (LVA)
O2 (DEU)
Antel (URY)
MegaFon (RUS)
Kolbi (CRI)
MTS (RUS)
Cosmote (GRC)
Vodafone (NLD)
O2 (CZE)
Vodafone (MLT)
LTC (LAO)
Turkcell (TUR)
Claro (NIC)
VIPnet (HRV)
Claro (URY)
Glo (NGA)
SFR (FRA)
OUR (SLB)
MTS (BLR)
Maxis (MYS)
Claro (ARG)
au (JPN)
Optus (AUS)
Unitel (MNG)
Wind (GRC)
Vodafone (ITA)
TT (TUN)
Celcom (MYS)
Du (ARE)
Zain (KWT)
T-Mobile (DEU)
Mobitel (LKA)
Rogers (CAN)
Vodafone (GHA)
Telstra (AUS)
OTA (DZA)
Play (POL)
GloBul (BGR)
Telenor (PAK)
Telenor (MNE)
Etisalat (AFG)
Orange (BEL)
AT&T (USA)
Velcom (BLR)
Orange (EGY)
Golan (ISR)
Beeline (RUS)
Movistar (MEX)
LMT (LVA)
Proximus (BEL)
Orange (ESP)
Vodafone (ROU)
Cellcom (ISR)
Movistar (ESP)
T-HT (HRV)
T-Mobile (AUT)
MTel (BGR)
Globe (PHL)
MTel (BIH)
Orange (FRA)
Ooredoo (TUN)
Movistar (CHL)
MobiCom (MNG)
DOCOMO (JPN)
Plus (POL)
MTN (ZAF)
Vodafone (TUR)
Telenor (DNK)
Nucleo (PRY)
Tele2 (SWE)
Orange (ROU)
T-Mobile (CZE)
Tigo (LKA)
Elisa (FIN)
Batelco (BHR)
MTN (NGA)
Claro (HND)
Tele2 (LTU)
MTC (VNM)
Orange (MDA)



O2 ranks last out of 320 operators in 100 countries

Source: NERA Economic Consulting

Notes: Includes only currently usable spectrum (excludes 1400 MHz). Includes 450 MHz, 700 MHz, 800 MHz, 850 MHz, 900 MHz, 1800 MHz / PCS, 2100 MHz / AWS (all FDD), 2600 MHz (FDD and TDD), and 2300 MHz (TDD). We exclude 1900 MHz TDD holdings, as the ecosystem path for this band is not yet clearly established. MNOs with less than 4% subscriber share are excluded.

4.2. Spectrum cap analysis

One explanation why the UK is such as outlier with respect to spectrum asymmetry may be differences in the approach of Ofcom and other regulators with respect to applying remedies in spectrum awards. To test this, we compared potential auction outcomes in terms of spectrum share across a sample of 14 auctions in 10 different countries, and also compared this against Ofcom's five options for competition measures for the PSSR award. Specifically, we looked at the maximum and minimum spectrum shares possible for existing operators. For fair comparison, we limited our sample to awards where there were four national operators at the time of the auction.

The results are shown in Table 3. We show the actual auction outcome and compare this to results for two alternative cases:

- Case 1: Largest operator in terms of spectrum share buys spectrum up to the relevant cap. The remaining spectrum is split evenly among the other three operators. Case 1 explores the extent to which an auction allows a single operator to unilaterally block other operators from purchasing spectrum.

- Case 2: Same as Case 1 but, in addition, the second largest operator in terms of spectrum share buys residual spectrum up to the relevant cap or limit of availability, whichever is smaller. The other two operators split any remaining spectrum evenly. Case 2 explores the extent to which two operators together could block other operators from purchasing spectrum.

Table 3: Hypothetical spectrum share outcomes for four-player market auctions

			Pre-Auction		Case1		Case 2		Actual Outcome	
Auction	**Year**	**MHz Available**	**Maximum % held by MNO**	**Minimum % held by MNO**	**Maximum % held by MNO**	**Minimum % held by MNO**	**Maximum % held by MNO**	**Minimum % held by MNO**	**Maximum % held by MNO**	**Minimum % held by MNO**
Denmark 1800 MHz	2016	130	28%	23%	32%	21%	32%	18%	28%	23%
Denmark 800 MHz	2012	60	29%	20%	29%	18%	30%	18%	29%	18%
Denmark 2600 MHz	2010	190	30%	18%	36%	17%	36%	15%	29%	20%
Ireland Multiband	2012	280	25%	25%	33%	15%	33%	10%	30%	20%
Italy Multiband	2012	290	27%	20%	33%	17%	32%	15%	26%	22%
France 700 MHz	2015	60	30%	17%	30%	17%	30%	15%	30%	18%
France 800 MHz	2011	60	29%	19%	31%	17%	31%	17%	30%	17%
France 2600 MHz	2011	190	29%	15%	33%	15%	33%	13%	29%	19%
Germany Multiband	2011	360	26%	24%	62%	13%	62%	11%	27%	23%
Netherlands Multiband	2012	340	29%	21%	75%	6%	75%	6%	33%	13%
Singapore Multiband*	2017	175	29%	13%	33%	13%	33%	10%	TBD	TBD
Sweden 1800 MHz	2011	70	28%	24%	30%	22%	30%	21%	30%	22%
Sweden 800 MHz	2011	60	32%	21%	37%	18%	37%	18%	32%	22%
UK Multiband	2013	250	39%	21%	37%	15%	37%	12%	40%	13%
UK PSSR: Option A	2017	190	42%	14%	51%	12%	51%	11%	TBD	TBD
UK PSSR: Option B	2017	190	42%	14%	51%	13%	51%	13%	TBD	TBD
UK PSSR: Option C	2017	190	42%	14%	43%	15%	43%	11%	TBD	TBD
UK PSSR: Option D	2017	190	42%	14%	51%	13%	51%	13%	TBD	TBD
UK PSSR: Option E	2017	190	42%	14%	32%	18%	32%	18%	TBD	TBD

Source: NERA Economic Consulting

Notes: We highlight cases in yellow where an auction outcome could have resulted in a 4th operator with a spectrum share below 15%. * Singapore auction is scheduled for 2017.

The purpose of this exercise is to test how restrictive the spectrum cap regime is. We make no consideration as to whether an outcome is plausible, given the likely business cases of the participants.

We find evidence that across the sample auctions, Ofcom takes a relatively relaxed approach to spectrum asymmetry, permitting outcomes that are often eliminated by spectrum caps in other jurisdictions. This may reflect a greater willingness on Ofcom's part to trust the market to produce efficient outcomes (notwithstanding evidence that the UK 4G auction in 2013 did not produce an efficient outcome).

Across the sample of 14 auctions, under Case 1, there are eight auctions where it was impossible for the fourth operator to be left with a spectrum holdings share of 15% or less, and six cases where this is/was possible, including the UK 4G auction. Many of these cases are auctions where the fourth largest player is/was a new entrant with low market share: France (2011), Netherlands (2012), and Singapore (2017). Such an outcome is also possible for the PSSR award under all remedy proposals except Option E. In three auctions, it was possible for two operators to fall below 15% spectrum share: Germany (2010), Netherlands (2012), and UK (2013). Turning to Case 2, the number of auctions where a 4th operator could be left with holdings under 15% rises to six, including Ireland (2012) and Italy (2012).

The maximum permitted spectrum share is also higher in the UK than many other countries. In the UK 4G auction, this was 37.3%. For the PSSR award, Ofcom has proposed de facto maximum spectrum share of usable spectrum of up to 51% (Options A, B and D). In our sample, this level has only been exceeded by Germany (2010) at 62% and Netherlands (2012) at 75%. For all other awards, the maximum spectrum share is in a 27%-37% range.

In practice, the UK 4G auction was the only completed auction in the sample to produce such a highly asymmetric outcome. Apart from the Netherlands, where new entrant Tele2 (13%), was expanding from a low base, the fourth operator secured a share of spectrum from 17%-23%, compared to 13% for H3G UK and 16% for O2 UK. Meanwhile, the maximum spectrum share following other auctions ranged from 26%-33%, compared to 40% for EE in the UK (excluding spectrum won by BT).

In conclusion, while the UK is not alone in permitting very asymmetric outcomes from spectrum auctions, it is unusual in having them actually come to pass. Arguably, as we set out in Section 3, Ofcom exacerbated this risk through its choice of a CCA format and other auction rules for the UK 4G award. Looking forward, it is exposing itself to similar risk for the PSSR award, albeit with an auction design that may be (somewhat) less vulnerable to strategic bidding.

4.3. Examples of operators with 10-15% of total spectrum holdings

In Annex 6 of the Consultation, Ofcom identifies six mobile operators across Europe with a national share of spectrum below 15%. Ofcom presents them as potential evidence to support its definition of a credible national operator requiring only 10-15% of spectrum holdings. However, a closer look at these operators, presented below, reveals they are very poor comparators for the UK market. In every case, there are special circumstances, for example because they have future options to expand spectrum (Telemach), have other options for managing capacity, such as roaming or MVNO agreements (Free and Tele2), turned down options to buy spectrum owing to financial difficulty (T-2 and Yoigo), or have been sold to another operator (Ziggo).

We conclude that there is no evidence from other markets to support Ofcom's assertion that a spectrum share as low as 10-15% is viable from a long-term perspective. At best, it could be argued that this may be adequate to support the launch of a new operator, especially one that can launch with 4G technology and does not require spectrum for legacy 2G or 3G use.

Tele2 (Netherlands)

Tele2 began as an MVNO in the Netherlands. In December 2014, it announced plans to build a nationwide 4G network; it launched in 2015 with ambitions to reach nationwide coverage by March 2016.[29] As of June 2016, it had a market share of 4.9%, but this is likely to grow.

Tele2's entry into the Dutch market has been facilitated by government intervention:

- **Reserved spectrum**. Tele2 holds two chunks of prime 4G spectrum: 2x10 MHz at 800 MHz and 2x20 MHz at 2600 MHz. Although this is only 12.5% of total usable spectrum in the Netherlands, this represents a much higher proportion of spectrum currently in use for 4G provision. It was able to acquire these spectrum blocks at a low price, facilitated by reservations for entrant operators in successive auctions in 2010 and 2012. We note that the entrant reservation in 2012 also had the effect of intensifying competition for residual spectrum amongst the three larger operators, who together spent EUR 3.8 billion in an exceptionally competitive process. In this context, it seems rather unlikely that Tele2 would have been able to afford to buy any spectrum in these auctions absent competition measures.

- **MVNO and site-sharing deals.** Tele2 has an MVNO relationship with T-Mobile that enables it to service 2G and 3G customers. It has "*no plans for a network delivering 2G/3G* services".[30] For its 4G network, it also benefits from a site-sharing agreement with T-Mobile Netherlands, which it cites as important to its ability to compete with the larger incumbents.[31]

Given Tele2's modest market share, it has no immediate need for more spectrum, especially given that its share of 4G holdings (if one excludes spectrum used by other operators to service legacy 2G and 3G use) is well above Ofcom's 15% threshold. If it is successful and establishes itself as a credible competitor, it will eventually need more spectrum. With the Dutch auction of 700 MHz and other bands forthcoming, it remains to be seen whether it will again benefit from government intervention to support further expansion of its spectrum holdings.

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[29] "Tele2 AB presents 4G plans for the Dutch Market." December 12th, 2014. See, http://www.tele2.com/media/press-releases/2014/tele2-ab-presents-4g-plans-for-the-dutch-market/.

[30] "Tele2 starts data revolution in Dutch Market." November 11th, 2015. See, http://www.tele2.com/media/press-releases/2015/tele2-starts-data-revolution-in-dutch-market/.

[31] "Tele2 AB: T-Mobile and Tele2 to share antenna sites in the Netherlands." August 14th, 2013. See, http://www.tele2.com/media/press-releases/2013/tele2-ab-t-mobile-and-tele2-to-share-antenna-sites-in-the-netherlands/.

Ziggo (Netherlands)

Ziggo is cited by Ofcom as an example of an operator with a spectrum share below the 10-15% range. However, it also acknowledged that it was never a credible MNO (CD §4.128). Ziggo acquired 2x20 MHz in the 2.6 GHz band through an entrant reservation in the 2010 auction. Ziggo never attempted to roll out a nationwide mobile infrastructure but did launch a LTE mobile network for business users in May 2012.[32] Ziggo subsequently agreed to an MVNO agreement with Vodafone in 2013, and thereafter made no other plans to become a nationwide mobile competitor.[33] It was acquired by Vodafone Netherlands and the merger has been accepted with concessions relating only to divestures of fixed-line businesses.[34]

Yoigo (Spain)

The history of Yoigo is filled with financial troubles and delayed network launches. Yoigo acquired a 3G licence in 2000, but a full network launch was delayed until late 2006 owing to financial difficulties. Its subscriber base reached a peak of 3.5 million subscribers in the Q2 2014 (6.4% market share), but has since declined to 3.25 million subscribers (5.8% market share).

The government has made repeated attempts to help Yoigo towards credibility with favourable spectrum concessions. Yoigo acquired additional, technology-neutral spectrum in 2011 via a beauty contest. As part of the concession, Yoigo committed to investing EUR 300 million in nationwide infrastructure. Yoigo had a further opportunity to acquire spectrum in the 4G auction, including a de facto reservation of 2x5 MHz in the 900 MHz band, but it declined to participate. After the 4G auction process, Yoigo’s spectrum share fell to 10.8% of usable spectrum.

Yoigo was previously owned by TeliaSonera, which made repeated attempts to sell the business. In 2013, it sold its stake to Grupo MASMOVIL, a fixed-line and MVNO operator in Spain. It remains to be seen whether the new ownership can improve on its disappointing historic performance. To do so, it will surely require more spectrum, so as to offer a competitive 4G service.

T-2 (Slovenia)

T-2 is Slovenia’s 4th operator, but is no longer recognised as a credible competitor. As of September 2016, T-2 has only a 3.2% market share, despite obtaining a 3G licence some ten years earlier.[35] T-2 has had a long history of financial struggles. In 2011, it entered into a debt restructuring plan totalling EUR 180 million that allowed the company to narrowly avoid the

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[32] See, https://www.telegeography.com/products/commsupdate/articles/2012/05/03/ziggo-launches-dutch-lte-mobile-network/.

[33] See, https://www.telegeography.com/products/commsupdate/articles/2013/09/18/ziggo-launches-voicedata-mvno-service/.

[34] See, http://europa.eu/rapid/press-release_IP-16-2711_en.htm.

[35] See, https://www.telegeography.com/products/commsupdate/articles/2006/09/28/t-2-si-mobil-confirmed-as-new-3g-licensees-mobitel-denied-extra-umts-spectrum/.

Slovenian government assuming control.[36] It was forced back into bankruptcy in March 2016.[37]

T-2 chose to sit out the Slovenian 4G auction, despite spectrum caps which de facto reserved a modest portion of the spectrum for one of the two smaller operators. The fact that the regulator did not offer a larger reservation may reflect an expectation that T-2 would not participate, owing to its financial difficulties. As a result, T-2 continues to hold just 2x15 MHz in the 2100 MHz band (5.3% of usable spectrum).

Telemach (Slovenia)

Ofcom cites Telemach (formerly Tusmobil) as an MNO with 10-15% spectrum share in a four-player market that has been able to grow market share despite a low spectrum share (CD §4.130). However, given the weak position of T-2, it would be more appropriate to consider Slovenia as a three-player market. Notwithstanding this point, we concur that Telemach is a credible player, but we note that it has a clear path to pick up additional spectrum as it grows its business.

Telemach’s growth has been assisted by spectrum concessions and reservations that enabled it to secure spectrum at reserve price without competition from the two largest operators. In the 2014 4G auction, owing to the non-participation of T-2, Telemach had the luxury of only buying the 50 MHz spectrum it immediately needed to support its customer base. Looking forward, with no other new entry likely, Telemach has options to acquire vacant spectrum in the 1800 MHz and 2.1 GHz bands. In December 2016, Telemach exercised an option to acquire 2x5 MHz of additional spectrum in the 2.1 GHz, which lifted its spectrum share above 15%. If it exercises further options, it can lift its share above 20%.

Free (France)

Free is cited by Ofcom as an example of a MNO with a 10-15% usable spectrum share that has been able to rapidly increase market share. Free has clearly established itself as a credible player but its success has been greatly aided by government policies with respect to spectrum reservations and mandated roaming access to a competitor network. In particular, Free had never truly been constrained by its spectrum share, owing to its ability to shift traffic on to competitor networks. More recently, helped by spectrum caps in successive auctions, Free has raised its share of usable spectrum to 18.4%, in excess of its market share of 17.9%, and has overtaken Bouygues to become France’s third largest operator.

Free began business with just 2x5 MHz in the 2100 MHz band, but it has steadily acquired additional spectrum by direct award – 2x5 MHz at 900 MHz and 2x15 MHz at 1800 MHz – and through auction – 2x20 MHz at 2.6 GHz and 2x10 MHz at 700 MHz. It has been aided by relatively tight spectrum caps which, in particular, restricted the ability of the two largest operators, Orange and SFR, to expand their spectrum shares. Most recently, the 2015 700

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[36] See, https://www.telegeography.com/products/commsupdate/articles/2011/11/29/t-2s-debt-restructuring-plan-approved-altnet-avoids-receivership/

[37] See, https://www.telegeography.com/products/commsupdate/articles/2016/03/08/slovenias-t-2-forced-back-into-bankruptcy/.

MHz auction limited all operators to 2x30 MHz across the 700 MHz, 800 MHz, and 900 MHz bands, including existing holdings. This had the effect of constraining all bidders except Free to winning to more than 2x10 MHz, whereas Free could bid for up to 2x15 MHz. Free eventually won 2x10 MHz, outbidding then third operator Bouygues.

In 2011, Free was the only operator not to secure 800 MHz, but it befitted instead from a provision guaranteeing it access to a roaming deal with another operator. After lengthy negotiations, Free agreed to a 2G/3G roaming agreement with established operator Orange France. This deal was very important in establishing Free as a credible competitor within France, and gave Free time and money to build its spectrum share. For example, it has been reported that some 97% of calls made by Free Mobile's customers were carried by Orange's network in 2012 causing capacity constraints on Orange's network.[38] Orange and Free have agreed to phase out the roaming agreement from January 2017 and end all agreements by 2020.[39] Free warned subscribers of lower 3G speeds from September 2016 onward owing to the end of previous roaming agreements.[40]

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[38] "Orange France losing patience with Free Mobile – report." Telecoms.com. February 14, 2012.

[39] "Free Mobile-Orange to end roaming agreement." Mobile World Live. June, 16, 2016, https://www.mobileworldlive.com/featured-content/home-banner/free-mobile-orange-to-end-roaming-agreement/.

[40] See: https://www.telegeography.com/products/commsupdate/articles/2016/08/01/free-warns-subscribers-of-lower-3g-speeds-from-1-september/.

5. Investment in networks is not a sufficient substitute for spectrum to support growth in 4G data usage

[✂] REDACTED. However, rapid growth in data combined with limitations on the scope for further technological advances mean that relationships and trends that have held true for many generations of cellular technology are coming to an end. While it is difficult to apply fundamental limits directly to the complex multi-user multi-cell radio environments, there is general agreement that current 4G systems are close to the theoretical Shannon limit. Attempts to design a “new radio” for 5G have not, to date, resulted in any material improvement in spectrum efficiency, illustrating the difficulty of finding further gains. As a result, Ofcom’s decisions on spectrum allocation have the potential to have a much greater impact on the competitive landscape than they have in the recent past.

This section is set out in five parts:

- In Section 5.1, we consider the rate of growth in demand for cellular data, and how these growth rates will affect both the industry and individual operators. We argue that once a network has reached capacity, high data growth rates imply congestion and deterioration in service quality within a very short time-period. Waiting for problems to occur before addressing them will result in significant subscriber discontent.

- In Section 5.2, we present evidence that spectrum efficiency achieved by macrocells is declining in urban areas. The implication is that spectrum constrained operators, [✂] REDACTED, cannot address their problem by building more macrocell sites and densifying their network. For these operators, refarming of 2G/3G spectrum is the only approach able to deliver large capacity gains [✂] REDACTED.

- In Section 5.3, we discuss a wide range of techniques, such as MIMO antennas and carrier aggregation, that can be used to improve the efficiency of spectrum use in existing macrocells. We show why these techniques will not provide material further gains in performance. Looking forward, there are no grounds for expecting that new algorithms or technology will arise that will resolve this problem. In any case, congestion would be very severe by this time.

- In Section 5.3.4, we look in detail at the issues surrounding small cells and show both intuitively and through a detailed model how small cells perform in a dense urban cellular network. We conclude that small cells are not a viable substitute for macrocell deployment in dense urban areas, and the incremental benefits they can deliver are typically modest. They are most effective if different frequencies can be deployed at the microcell level, an option unavailable to spectrum-constrained operators.

- In Section 5.4, we discuss the implications of this analysis for spectrum policy and for consumers. [✂] REDACTED.

5.1. Demand forecasts

Demand for mobile data is currently growing at an exceptional rate, placing unprecedented pressure on mobile networks. For example, according to Cisco, UK mobile data traffic grew 57% in 2015.

There is some uncertainty regarding how far and how fast data rates will rise over the next ten years. This is illustrated in Figure 8, which compares the bullish forecasts of manufacturers Cisco and Ericsson against Ofcom's more conservative predictions:

- The Cisco VNI forecast[41] for the UK predicts that mobile data traffic will grow to 600 PB per month by 2020, a 5.5 fold increase from the current rate of 108 PB per month. This equates to an annual growth rate of 47%. It further predicts that UK mobile data traffic will grow two times faster than UK fixed IP traffic from 2015 to 2020.

- The Ericsson mobility report[42] from November 2016 predicts an increase to 22 GB per month per user for mobile traffic in Western Europe by 2022. Applying this to the UK market equates to 1,800 PB per month.

- Ofcom provided a set of forecasts in June 2016 in its Mobile Data Strategy. It said that:

  > "*Today data traffic is 0.8GB per connection per month; this equates to 1.3GB per adult population per month. We have considered various potential scenarios of traffic per pop of 10GB, 20GB and 40GB per month [in 2025]. These 3 scenarios imply an annual growth rate of 25%, 33% and 42% between 2014 and 2025. These figures are higher than the forecast we quoted in our 2014 statement (22% annual growth rate between 2014 and 2030). This is to reflect the new use cases and the impact they may have on mobile data traffic, as 4G penetration and use increases and we start seeing early adoption of 5G services.*"[43]

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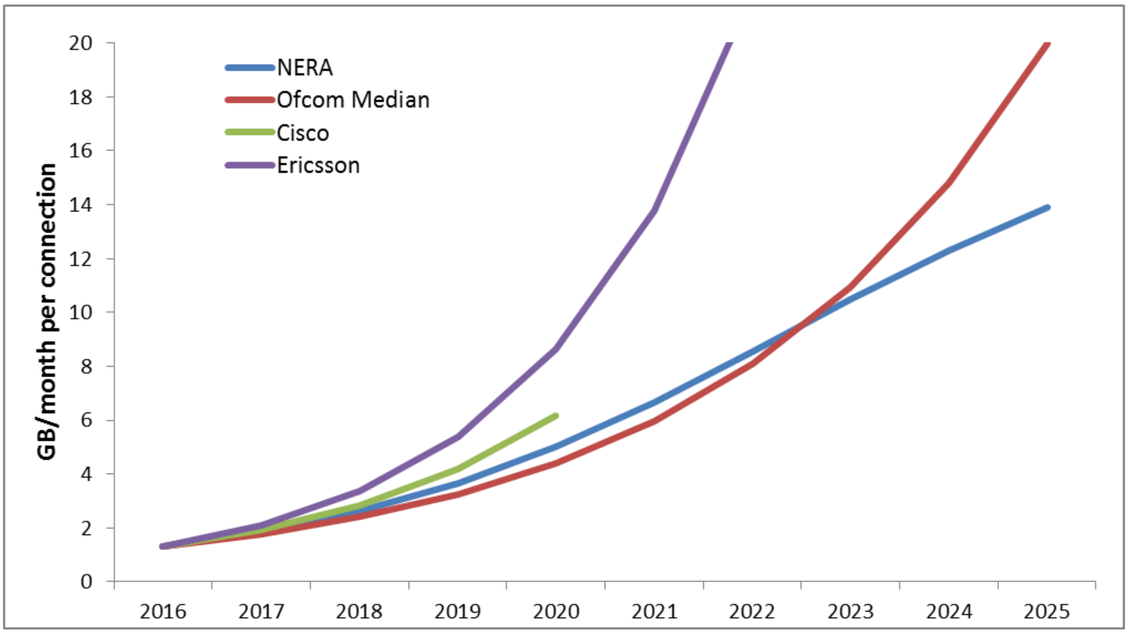
[41] See http://www.cisco.com/c/m/en_us/solutions/service-provider/vni-forecast-highlights.html# for a version of the forecast optimised for the UK.

[42] See https://www.ericsson.com/assets/local/mobility-report/documents/2016/ericsson-mobility-report-november-2016-rwe.pdf

[43] See https://www.ofcom.org.uk/__data/assets/pdf_file/0033/79584/update-strategy-mobile-spectrum.pdf

Figure 8: Forecast demand for UK mobile data, 2016-25



Source: Cisco, Ericsson, NERA Economic Consulting, Ofcom

For our own modelling in Section 6, we have adopted a conservative projection of demand growth, which is closely aligned with Ofcom’s thinking (see Figure 8). We have deliberately adopted Ofcom’s relatively conservative approach for two reasons. First, we want to demonstrate that even under conservative assumptions for data growth, spectrum-constrained operators face potentially serious capacity problems. Second, under a more aggressive data consumption model, such as the Ericsson view, it would be the case that all operators become capacity constrained without additional spectrum. The conservative approach allows us to develop a model that more clearly signposts the impact of different capacity constraints between operators.

Our national forecast is an aggregation of forecast demand growth across the four operators, as illustrated in in **Error! Reference source not found.**. As of 2017, the four operators have rather different profiles with respect to average data consumption per user.[44] Notably, although H3G has by far the smallest customer base, it has much higher average traffic rates. Looking forward, we expect [✂] REDACTED.

Given the similarity between our forecast and Ofcom’s own forecast, and our conservative assumptions versus Cisco and Ericsson, we believe this should address any concerns from Ofcom that we are overstating demand.

Even under our conservative assumptions, the volume of data traffic is set to grow six-fold over the next ten years. [✂] REDACTED. When traffic is growing this fast, a network can tip from surplus capacity to congestion in a very short space of time, resulting in a rapid

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[44] Data traffic on MNO networks is from Enders analysis cited in the Consultation (Figure A7.13). Subscriber data provided by Ofcom and includes MVNO traffic.

deterioration in quality of service if not addressed through network expansion. As we show in Section 6.3, [✂] REDACTED.

5.2. Limits on macrocellular capacity

[✂] REDACTED.

5.2.1. Current macrocellular capacity

[✂] REDACTED.

The overall implication of this section is that spectrum efficiency in lower frequency bands is likely to fall rather than grow in coming years. Hence, estimates made of overall network capacity based on current frequency bands and levels of spectrum efficiency are likely to be optimistic. [✂] REDACTED.

5.2.2. Refarming

There has been a significant improvement in spectrum efficiency when moving from one generation of technology to the next. Moving from 2G to 3G for data transmissions is around twenty times as efficient, and moving from 3G to 4G a further 2.5 times better (depending on the exact version of each of the different generations considered). Hence, refarming spectrum used for earlier generations to the latest generation can bring substantial gains.
[✂] REDACTED.

5.2.3. Planning issues

We have previously presented evidence to Ofcom to show that one of the most significant restrictions on deploying more macrocells is the difficulty in finding appropriate sites. Since our last submission there have been changes to the planning regulations and code of best practice. These are positive and will help with planning. It is now possible to deploy some sites under ‘permitted development with prior approval’ that would have previously needed full planning. However, MNOs are still dependent on local authorities for timeliness and approval, as well as being able to find a suitable site and willing landlord in the right location. O2 tell us that this is particularly challenging for traffic hot spots in urban areas, including areas in central London. In summary, the planning issue has eased slightly but remains a major impediment to deploying more cells in dense areas.

5.3. Limitations of technology options to enhance capacity

In this section, we consider the capacity enhancement tools [✂] REDACTED. We consider approaches which we believe have merit, such as six-sector operation and MIMO antenna systems, and show that these are already being used to the extent possible. We then discuss approaches mentioned by Ofcom that we do not consider to be practicable or even relevant, including Coordinated multi-point transmission (CoMP), carrier aggregation and self-optimising networks (SONs).

5.3.1. Approaches which are effective but already deployed

MIMO antennas

Using multiple antennas enables capacity gains through spatial diversity.[45] If there are multiple radio paths from the base station to the device then the differences between the signals received at each antenna can be used to extract additional information. In theory, the capacity gains from MIMO are equal to the lowest number of antennas on either the base station or device. So, for example, 2x2 MIMO, with two antennas at the base station and two at the device, is up to twice as efficient as non-MIMO transmission. 4x4 MIMO is twice as efficient again. However, 4x2 MIMO is only as efficient as 2x2 MIMO unless the extra elements are used for other purposes such as beam forming. In practice, gains are much less than this, as radio conditions are less than optimal and the necessary understanding of the channel conditions imperfect. [✂] REDACTED. MIMO tends to be more effective with TDD where channel measurement is simpler because the uplink and downlink can be assumed identical. Hence, higher order MIMO may be best deployed in TDD bands, such as 2.3 GHz or 3.4 GHz.

For MIMO to be effective, antennas need to be well-spaced so they receive different signals. Typical recommendations are for antenna spacing of 5-10 wavelengths at the base station and 0.5 - 1 wavelengths at the receiver for optimal performance. At 900 MHz, a wavelength is 30cm, requiring 1.5m – 3m spacing at the base station. At 2.3 GHz, this falls to 12cm, reducing distances to 60cm – 1m.

[✂] REDACTED. At lower frequencies, physically separate antennas are needed to get sufficient spacing, whereas at higher frequencies a single structure can be deployed with multiple antennas within it. Practically, deploying additional antennas onto existing sites is very difficult owing to physical constraints and landlord permissions. Hence, increased MIMO is only practical in the higher bands at 1800 MHz and above. It is also not generally practical where six-sector sites are deployed (see below) owing to the lack of space generally available for additional or enlarged antennas at these sites.

MIMO used for beam forming can also improve range as the energy is now focussed in a beam and so travels further. This might be important for use of 3.4 GHz spectrum where propagation is lower than at 2.3 GHz. Early trials suggest that using eight beam-forming elements at the base station enables sufficient range to allow 3.4 GHz to be usefully deployed on macrocell sites in high-capacity areas. These antennas are relatively small, enabling deployment on most sites and are already becoming available. This form of MIMO can only work effectively in TDD spectrum as the terminal device cannot focus its return signal and so the base station has to use the same configuration to receive as was used to transmit. Hence, it

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[45] There are two ways that MIMO can increase capacity. The first is “classic” MIMO where multiple paths between the transmitter and receiver are created, with different data sent via each path. This requires as many antennas at the device as at the base station. The second is beam-forming where the antennas are used to form a more focussed beam of radio energy which reduces the interference levels to others in the cell, enabling greater capacity. Beam-forming typically only occurs at the base station and does not require additional antennas at the terminal. So, for example, a 2x2 MIMO deployment would be entirely classic MIMO, whereas a 4x2 MIMO deployment might use two of the base station elements for classic MIMO and two for beamforming.

cannot be deployed on most current spectrum but is a valuable tool for 2.3 GHz and 3.4 GHz deployments, as well as for 2.6 GHz TDD.

In short, classic MIMO is fundamentally limited by both difficulties in antenna installation at the base station and a lack of devices with multiple antennas in the marketplace.
[✂] REDACTED.

Six-sector sites

Increasing the number of sectors on a cell is akin to deploying more cells – it effectively divides a single cell into a number of pie-shaped cells. Most macrocells are initially deployed with three sectors which typically provide a good balance between cost, practicality and capacity. Where needed, a three-sector cell can be modified to a six-sector cell. With theoretically perfect antennas and no building scattering this would bring gains of 100% but such antennas do not exist in practice and hence there is interference at the boundaries of each sector. Making the sectors narrower increases the percentage of the sector where interference is significant. [✂] REDACTED. Further, the increased interference into neighbouring cells can also reduce the capacity available there.

The deployment of six-sector sites requires the addition of extra antennas to the sites: three larger dual beam antennas to replace the existing three antennas; or three additional antennas. As with MIMO, deployment is difficult or impractical on many sites, owing to physical constraints, planning and landlord permissions. [✂] REDACTED.

The deployment of six sectors also precludes the deployment of increased order MIMO. This is because the number of antennas that would be needed on the site to accommodate six sectors would make it too difficult to then accommodate the additional separate antenna(s) per sector required for MIMO. We anticipate that the best strategy to improve capacity for an operator with a mix of MIMO and six sector sites would be to deploy TDD-MIMO at 2.3 GHz and later at 3.4 GHz, which provides substantially greater capacity uplift than adding FDD MIMO or six-sector deployments. [✂] REDACTED.

5.3.2. Approaches which are impractical

CoMP

CoMP is a technique where signals to a mobile device are sent simultaneously from multiple base stations. Its primary benefit is to enhance service to mobile devices at cell edge where signals from multiple base stations are often of approximately equivalent strength. This does have some capacity benefits by reducing the loading that such devices place on the network. However, CoMP is an untried technique and any gains are uncertain.

CoMP requires:

- a suite of features and algorithms for co-ordinated transmission between cells to reduce interference;
- fibre backhaul to base stations and a centralised RAN architecture to enable effective coordination – this would be a very substantial undertaking; and

- terminals that can support CoMP which are not currently available.

In short, CoMP is still a topic for research and not one that can deliver short-term capacity gains into the network. Whether it is practical or economic in the long term remains to be seen.

5.3.3. Approaches which are not relevant

Carrier aggregation

Carrier aggregation (CA) allows devices to receive on multiple carriers simultaneously. It is primarily used to deliver higher data rates and is not a capacity enhancement technique. It can, in principle, deliver small capacity gains through an ability to spread load more evenly across a number of bands.

Imagine a situation where an MNO has three LTE carriers in a sector. Active data users are assigned to one of the carriers such that there is an approximately equal number on each. This is akin to three check-outs at a supermarket where customers are assigned to a checkout on arrival. If, say, each carrier could deliver 10 Mbits/s and each customer required an average of 1 Mbits/s then Erlang C traffic calculations predict that for there to be less than a 1% chance of a subscriber having to wait then four subscribers could be assigned to each carrier, enabling 12 subscribers in total. Now imagine a situation where there is carrier aggregation which enables the network to move subscribers from one carrier to another, or share their load across multiple carriers. This is akin to subscribers in the supermarket selecting the checkout queue on arrival at the checkout. In this case, Erlang C predicts 18 subscribers could be served – a 50% improvement.

However, in real networks there are many more active subscribers per carrier and blocking rates above 1% are routine. In the case where there are 30 subscribers per carrier and 5% chance of waiting is allowed, then blocking occurs at 21 subscribers per carrier (63 in total) for fixed allocation and 74 flexible allocation – a 17% improvement. Even this is an overstatement as networks without carrier aggregation can hand subscribers off from one carrier to another to dynamically balance load. This process takes slightly longer than a shift in carrier aggregation usage so is slightly less efficient but nevertheless resolves imbalances quickly. As a result, gains of over 10% in capacity through carrier aggregation are very unlikely.

Further, only a subset of devices currently support CA in the bands that O2 has available. This will increase over time, but as a result for the coming few years any gains in capacity will be of the order 1-2%.

There are penalties with CA. In particular, it requires more signalling information than non-CA operation to set up and maintain the multiple frequency bands, creating an overhead. This can offset any small multiplexing gains.

[✂] REDACTED.

SONs

Another technique mentioned by some is self-optimising networks (SONs). These are networks where the optimisation of the radio and network parameters is performed automatically by software rather than manually by experts. SON can be particularly valuable where the allocation of a particular frequency to a cell as part of a frequency-reuse deployment is needed. However, 4G networks use single-frequency allocation where all cells use the same channels and hence there is no frequency optimisation that can be performed. Optimisation can be valuable in enhancing parameters such as neighbouring cell lists, making handovers work better and so improving the user experience. As such, it is a valuable tool for MNOs, but not one that has the ability to enhance capacity to any material degree.

5.3.4. Longer-term capacity enhancements

Ofcom have indicated that they believe that capacity enhancements will be found that will result in gains in the medium to longer term, saying that:

> "*Other LTE-Advanced technologies will bring incremental capacity improvements but are currently in their infancy so the exact extent of the benefits in real networks that will be realisable is a little uncertain at this stage, although we expect algorithms and benefits to increase over time*." (CD §A8.52)

In this section we show why there is little scope for such improvements by citing research on the 5G "new radio" which might replace 4G after 2020 and show that at present the capacity gains are near-zero. We consider the 3GPP roadmap and show that there are no items on this roadmap that we have not previously considered and which might make a significant change to capacity. We also express the view that algorithmic changes have not made any material improvements in the last four years. Finally, we consider Licence-Assisted Access (LAA) and show why it is very difficult for operators which do not have an associated fixed line business to utilise this.

New radio interfaces

New radio interfaces are only implemented with new generations of cellular technology; therefore we do not expect to see any new radio until 5G is deployed. It is very unclear when this might occur, but at present we do not anticipate this happening before 2020 at the earliest and more likely 2022 or later. We discuss new radio solutions here in order to show that gains in spectrum efficiency are very hard to achieve.

Much research is currently underway to find a "new radio" (NR) that could be deployed in 5G. There is an overview of the work in the IEEE Communications Magazine of November 2016[46] where, for example, Xi Zhang et al present their findings on the waveforms for 5G[47]. These are shown in Figure 9, taken from their paper.

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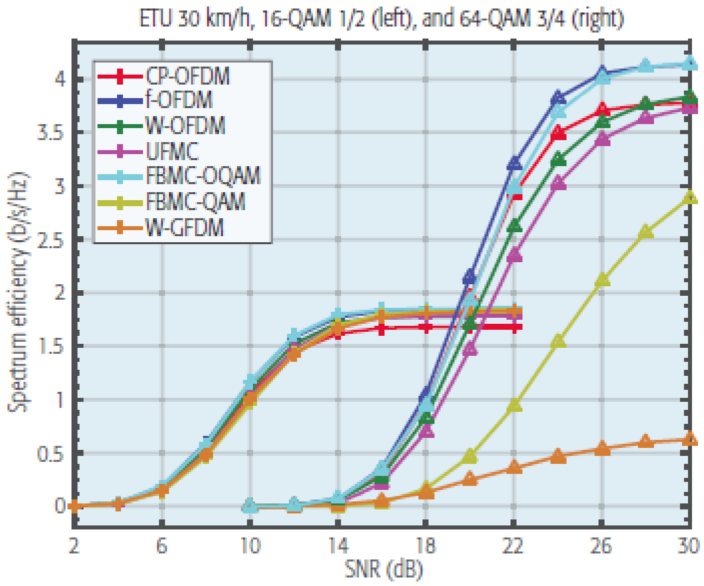
[46] IEEE Communications Magazine Vol 54 No 11, November 2016.

[47] Ibid pp 74-80.

Figure 9: Simulated spectrum efficiencies of various possible 5G new radio solutions



Source: IEEE Communications Magazine Vol 54 No 11, November 2016 pp74-80.

In this figure, the waveform used for LTE (shown in red) is termed CP-OFDM while the other lines represent alternatives under consideration. The figure presents two sets of data, those on the left are using modulation schemes suitable for low SINR operation, those on the right the converse.

The figure shows no material difference in any of the waveforms at low SINR, where macrocells operate in city centres. Even in the best case of high SINR at around 26dB (a very rare occurrence in a highly loaded network) the best solution – f-OFDM delivers around 4 bits/s/Hz compared to 3.7 for the current LTE waveform – a gain of about 8%. While it is possible that other waveforms will be discovered, time is now limited before the 5G standardisation work will require a selection of the waveform.

If no material improvement can be found even with the flexibility of a “clean sheet of paper” design, then it is inconceivable that improvements in the underlying LTE radio interface will transpire.

3GPP roadmap

Improvements in spectrum efficiency can typically only be implemented once they have been standardised. Hence, the standards roadmap provides a good guide to likely efficiency enhancement techniques. Here we consider the 3GPP roadmap which covers all aspects of 4G and 5G relevant to spectrum efficiency. We detail Release 13 (frozen in 2016), Release 14 (expected to be frozen in 2017) and Release 15 (expected to be frozen in 2018). No further releases beyond this are currently defined, but given that it often takes two or more years from a release being frozen to the earliest implementation, and three to five years for widespread availability throughout network and handsets, this pushes the 5G roadmap out to at least 2020 and more likely 2022 (see Section 5.6 for further discussion).

Release 13

In addition to enhancements to existing services and features, this release saw the completion of the first set of specifications covering mission-critical services, in particular mission-critical Push-To-Talk, the essential functionality for LTE to be used by ‘blue light’ services for private mobile radio voice communication.

Work continued on security issues to ensure that new services are free from the threat of hacking, denial of service attacks etc.

3GPP continued to work on the characterisation of carrier aggregation across additional band combinations to provide increased bandwidth within the limited frequency allocations to individual operators. Radio propagation was further improved by studies on Multiple-Input Multiple-Output antennas for both uplink and downlink, and on ever more sophisticated beam-forming.

A number of studies were conducted into the use of shared, unlicensed spectrum (particularly the 5 GHz Industrial, Scientific and Medical band). Work then began on specifications to complement LTE coverage over a licensed Primary Component Carrier via a Secondary Component Carrier using unlicensed spectrum.

Other major advances achieved with the freezing of Release 13 included enhancements to machine-type communications, public safety features, small cell dual-connectivity and architecture, indoor positioning, single cell point-to-multipoint and work on latency reduction.

Few of the features in this list are relevant for capacity. The key features for capacity enhancement are the improvements in MIMO antennas and the development of the LAA specifications which are discussed separately.

Release 14

Release 14 is focusing on Mission Critical enhancements, LTE support for vehicular communications (V2x services), enhanced LAA (eLAA), four-band carrier aggregation, inter-band carrier aggregation and more.

There are more than 30 studies in Rel-14, on topics such as:

- 5G requirements;
- Multimedia Broadcast Supplement for Public Warning System;
- User control over spoofed calls;
- Location services;
- Mission critical video and data over LTE;
- LTE support for V2X services;
- Enhancement for TV video service;

- Enhanced flexible mobile service steering (eFMSS);
- Home Routing Architecture;
- Emergency services over WLAN;
- Control and user plane separation of EPC nodes;
- Overload control for Diameter charging applications;
- Latency reduction techniques for LTE;
- High Power LTE UE for Band 41;
- Channel model above 6 GHz;
- Single radio voice call continuity (SRVCC) enhancements;
- Service domain centralization;
- Robust call setup for VoLTE subscriber in LTE;
- OAM (energy efficiency and SON for AAS-based deployments);
- UICC power optimization for machine-type communications (MTC);
- Requirements for Next Generation Access technologies; and
- Multi-Carrier enhancements for UMTS.

None of these appear to be related to capacity enhancement. Instead, they are a mix of additional services and user-specific features and preparation for 5G.

Release 15

Release 15 is predominantly focussed on the 5G New Radio (NR) and includes support for standalone and non-standalone NR operation. (Non-standalone NR in this context implies using LTE as control plane anchor. Standalone NR implies full control plane capability for NR.) Frequency ranges below 6GHz and above 6GHz are being studied.

Here the key capacity gains if any will come with the 5G new radio as discussed earlier.

Summary

There are no new features in the 3GPP roadmap for at least the next five years which will materially enhance spectrum efficiency. The closest are improvements to carrier aggregation, which is not primarily about capacity enhancement, MIMO antennas and LAA.
[✂] REDACTED.

Algorithmic changes

Algorithms are widely used in mobile networks to manage many aspects of performance such as handover, selection of frequency band, the use of various timers to manage handset power consumption, roaming and much more. Algorithms are rarely included within the 3GPP standards, instead they are supplied by equipment vendors as part of software updates and as a result tend to be proprietary.

Like all MNOs, O2 receives new software updates periodically and these tend to provide useful enhancements that improve user experience. However, over the last few years, we are not aware of any algorithmic improvements that have materially affected network capacity and nor do we anticipate that this will change in coming years.

Hence, we do not expect that algorithmic changes will enhance capacity.

LAA

Looking forward, another option is to use spectrum outside of the normal cellular range. The concept of LAA, including both LTE-unlicensed (LTE-U) and a more recent initiative called MuLTEfire, has been developed and discussed within the cellular community in recent years. These initiatives would allow MNOs to utilise the substantial amount of unlicensed spectrum at 5 GHz and other unlicensed bands that might be released in future.

There are many barriers that need to be overcome before this technology could be implemented and bring any benefits in alleviating congestion. Much unlicensed spectrum is already used by Wi-Fi routers and hence the amount of relatively clean spectrum that each MNO might gain will not generate a large increase in effective spectrum holdings. Using this spectrum might be relatively expensive as bespoke equipment will be needed but the capacity it provides may be less than equipment for other bands such as 3.4 GHz. With the uncertainty of access, it will be difficult to plan networks which rely on these bands for capacity, but reliability of service is one of the important requirements. There is a risk that an increase in loading in the 5 GHz band might displace traffic currently carried on Wi-Fi towards cellular as users seek a more reliable connection. This could, perversely, increase congestion on the cellular networks. Power levels are likely to be similar to Wi-Fi with resulting very small coverage area. Finally, handsets with this functionality are unlikely to be available for some years.

Because of the low power levels and high frequency, the range will be too short to viably deploy these frequencies on macrocells. The most likely deployment scenario is on Wi-Fi access points and other indoor small cells.[48] However, indoor small cells are rarely the capacity constraint in city centres, so adding further frequencies here will not materially improve overall capacity. If indoor small cells are already deployed then they will tend to have sufficient capacity using 4G frequencies as they will typically cover a relatively small number of users. If indoor cells are not already deployed, then the ability to use LAA does not change the incentives and difficulties of deployment.

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[48] For example, see press releases such as http://4g-portal.com/singtel-and-ericsson-will-trial-license-assisted-access

LAA might be most readily used by MNOs that also supply home Wi-Fi access points. Such MNOs could add LAA into these APs before supplying them to customers and then, subject to customer agreement, use LAA to provide coverage in the vicinity of the house, along the lines of OpenZone. EE therefore might gain the most from LAA, and yet it is the MNO with the largest spectrum holdings already.

In summary, at this stage, we believe that the use of unlicensed spectrum is unlikely to add substantial capacity for an MNO and is not a short-term solution.

5.4. Limits on scope for deployment of small cells

We previously presented evidence to Ofcom that showed why small cells were only able to increase capacity by a factor of about 100%. Ofcom responded that they did not believe the model we had used considered factors such as increased power level or siting of the base station closer to buildings in order to improve in-building penetration. We have further enhanced the model to examine increased power levels and different siting configurations and show that these make very little difference to the overall results, and that increased power levels are infeasible in any case as appropriate base stations are not available. Hence, we believe we have demonstrated through detailed modelling and analysis that small cells cannot deliver large capacity gains. Higher powers may also be a concern from a radiation hazard perspective given that small cell antennas are much closer to the general public.

In this section, we provide an intuitive description of the problem and then present a detailed model. We also discuss the findings of the recent NIC report which highlighted the difficulties and costs associated with small cell deployments.

5.4.1. Intuitive description of small cell operation

Cellular systems historically have delivered most of their capacity gains through a reduction in cell sizes. Replacing one large cell with ten smaller cells can deliver nearly a ten-fold increase in capacity through allowing frequencies to be reused in each of the new cells. By moving from networks where less than 10 cells covered an entire city to those where major cities can have many hundreds of cells then gains of 10 or even 100-fold have been realised.

When making cells smaller it is important that the radio signals from the base station propagate less far, otherwise they will cause interference in the new smaller cells which would decrease capacity.

Reduced range is achieved through a combination of:

- Reducing the transmitted power;
- Reducing the height of the transmitter; and
- Angling antennas downwards (“downtilt”).

In rural areas, mast height is typically within the control of the operator and downtilt of any required degree can be achieved. This is not the case in urban areas. Macrocell antennas are almost invariably mounted on rooftops which are typically many stories high. Downtilt is limited by the distance of the antennas from the building edge. There comes a point where rooftop mounting is incompatible with reducing cell size and cells have to be deployed below rooftop level. Such cells are known as “small cells” (or “microcells”).

This point represents a step-change in network design. Small cells have their coverage constrained by the buildings around them as they cannot radiate across the top of nearby buildings. They tend to provide coverage along the streets which they have visibility down. Instead of the approximately circular coverage of a macrocell they deliver linear coverage. Further, their range is generally restricted to around 100m in cities depending on the straightness of the streets and other blocking factors. **This step-change has critical implications in delivering capacity gains**. In particular, it prevents gains delivered by the previous approach of cell splitting being fully realised.

The primary implication is that unlike previous cell splitting where one macrocell was replaced by multiple smaller ones, the macrocell cannot be replaced by the small cells, only supplemented by them. This is because it is extremely difficult to deliver contiguous coverage across a city using small cells alone owing to the very large number that would be needed – typically some 50 to 100 per macrocell. Small cells are also poor at handling subscribers moving at vehicular speed owing to the frequent handovers needed and so such users are best handled by the macrocells. Finally, and most critically, small cells are relatively poor at providing in-building coverage. Close to the base station where the small cell can “see” well into the building then the penetration is good, but further away as the angle of the beam becomes more oblique to the building the penetration falls rapidly and in-building coverage tends to be provided by the macrocell which is more likely to have a better angle into the building. Also, with their low height, small cells can only illuminate the lower floors of buildings – typically the ground and first floor. In dense cities, most buildings have many more floors than this so much of the in-building traffic cannot be served by outdoor small cells.

This means that, in any given area, some percentage of the traffic will be handled by the small cells and the remainder handled by the macrocell. The percentage will depend on the degree of small cell coverage, the amount of in-building traffic and the amount of faster-moving traffic.

Imagine a situation where 50% of the traffic is captured by the small cells and that these cells have infinite capacity. The capacity constraint is now the macrocell. As the number of subscribers using it has halved then simplistically each subscriber can now transmit twice the amount of data and so the overall capacity of the network has doubled. However, the small cells will need to use some frequencies which previously could have been used on the macrocells. If half of the frequencies are assigned to the small cells then the macrocell now only has half the frequencies to handle half the subscribers and the net effect is no increase in capacity. This is despite the fact that the small cells are far from being congested. If traffic levels were allowed to rise then the 50% of users in the small cells would be served well, but the remaining 50% would experience increasingly severe blocking. Such an outcome would be intolerable for the blocked users who would have subscribed to a service that they were unable to receive.

The key question then becomes the percentage of traffic that can be handled by the small cells. This will depend on many variables but, for example, ABI and others estimate that more than 80% of all traffic originates or terminates indoors.[49] If small cells could only serve say 50% of the traffic on the ground and first floor and the average building in a dense city had six floors, then small cells could only carry 16% of the indoor traffic (13% of total). Even if they carried all the outdoor traffic this would amount to only 36% of the total load. In practice, small cells may be able to perform better than this if targeted at hotspots such as shopping malls.

One way to resolve this would be to deploy indoor small cells. But to be effective this would require at least one cell per floor of almost every building and many more for larger buildings. That would require many thousands of indoor small cells which would be very expensive and extremely difficult logistically with agreements needed with many different building owners. Attempts to deploy cellular systems indoors over the last 20 years or more have had limited success and there is little to indicate this will change in future. Indeed, the prevalence of (self-deployed) Wi-Fi within buildings is increasingly making cellular systems appear less relevant.

To summarise, the key change from previous splitting of cells into multiple smaller ones is the move from rooftop-mounted cells to street level cells. This creates a step-change in the coverage provided and requires the macrocell to remain in place. If a significant number of users prefer the macrocell then it is likely that it will become the constraining factor. Because small cells have limited outdoor coverage and poor indoor coverage it is very difficult for them to capture the vast majority of users. The net result is that their ability to increase capacity is limited. A simplistic assessment that they might attract 50% of the traffic in the cell shows that this can, at best, double the effective cell capacity.

5.4.2. Detailed modelling of small cell deployment

In Annex I, we present a detailed model of small cell deployments in LTE networks. The purpose of the model is to show why capacity gains are less than might be expected based on traditional models for densification of macrocells, and provide insights into optimal small cell numbers.

The key conclusions are:

1. Small cells are not a source of infinite capacity expansion. The best possible improvement is around 100% (2x) over a sectored 1km radius macrocell.
2. The optimal number and deployment strategy vary depending predominantly on the presence of hotspots in the sector and also the percentage of indoor subscribers. In most cases deploying more than around three small cells is not worthwhile.
3. A hot-spot strategy will nearly double the cost of carrying traffic in the sector on a $/bit basis compared to using a macrocell alone. A dense layer will result in a six-fold cost increase and a complete layer more than a ten-fold increase.

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[49] See https://www.abiresearch.com/press/abi-research-anticipates-building-mobile-data-traf/ , or http://www.smartbuildingsmagazine.com/news/only-2-of-buildings-have-dedicated-wireless-technology and many other sources.

4. Capacity improvements beyond these levels will require indoor picocells. These have not been modelled but typically improve capacity owing to the shielding offered by the building which reduces interference.
5. The situation is complex, requiring a cell-by-cell evaluation of optimal strategy.

The implications for MNOs are significant. It will not be possible to use outdoor small cells as a way to substantially add capacity in the manner previously thought. This could leave an MNO that has already deployed all of its spectrum and all other capacity enhancement approaches in a position where it is no longer able to grow capacity to meet growing demand absent being able to access additional spectrum.

5.4.3. The NIC report and other evidence

The National Infrastructure Commission (NIC) published its report "Connected Future" in December 2016. While primarily concerned with 5G, it addressed the issues of building small cell networks in city centres.

The report notes:

> "*The future of mobile looks different to the past and enabling that future will necessitate regulatory change. Delivering extensive coverage at high data speeds and with robust reliability, with each operator running a separate network, would require vast levels of investment. There must be an increased role for infrastructure sharing, not only to reduce the costs of network deployment where possible but to make best use of the limited supporting infrastructure such as street furniture in our towns and cities. Any regulation of network infrastructure should seek to be supportive of this sharing, whilst ensuring competition and fair access are maintained.*
>
> *[…] Taken together, these challenges suggest it would be unwise to assume that small radio cells will necessarily be cheaper or quicker to deploy than other types of cell architecture. Significant backhaul requirements together with the sheer volume of sites required will result in the need for significant investment. And urban restrictions such as local authority permits and traffic management needs could prove to be costly obstacles, causing delays and expense.*"[50]

We discussed earlier how small cells could only be effective if they captured the vast majority of the traffic within a macrocell but that this would require dense deployments. The NIC report confirms the cost and complexity of such deployments and suggests that they may need to be based on shared networks or similar to be economically and logistically viable. The changes and studies recommended by the NIC will take many years to be discussed and implemented during which time small cell deployment would be both difficult and potentially at risk of not being suitable for any shared networks or similar that might arise.

This is another strong argument why small cell deployment cannot be a short-to-medium-term solution to the need for additional capacity.

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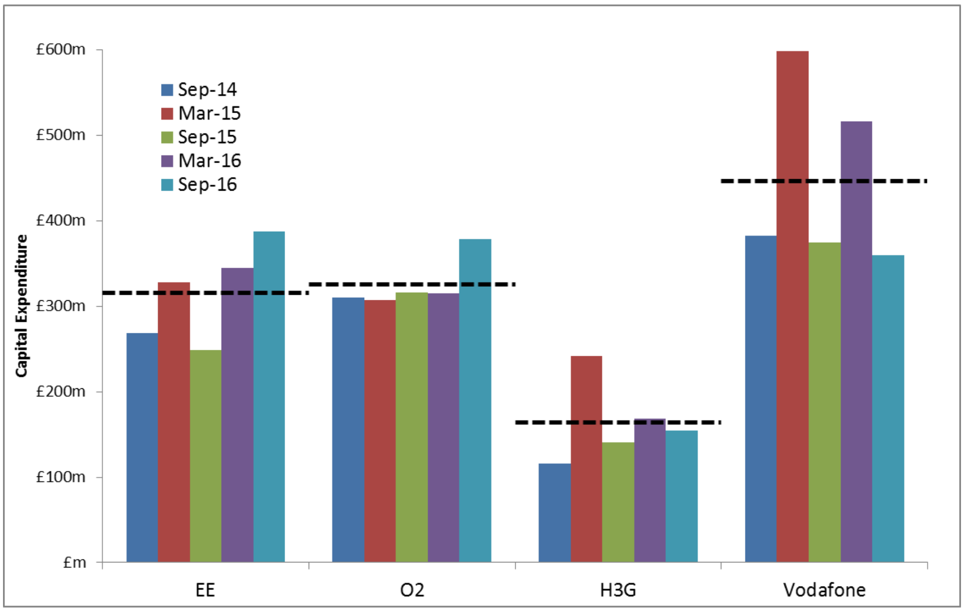
[50] "Connected Future", National Infrastructure Commission p. 20 and p.65, December 14 2016.

5.5. Implications for regulators and consumers

In this section, we have shown that MNOs have limited scope to grow their network capacity using either enhanced technology or additional cells. O2 is already aggressively refarming to the most efficient technology available and has deployed small cells up to the point of maximum significant gain. Other technologies such as carrier aggregation and CoMP do not deliver capacity gains or are not proven or available. However, customer demands are growing rapidly at a compound annual growth rate in the region of 40%. The only method that MNOs have available to them to meet these demands is additional spectrum.

There appears to be an implicit assumption in the Consultation that operators with poor capacity are under-investing in their network. However, we can find no evidence that this is the case for O2. For example, in Figure 10, we show that O2's capex investment over the last two years is equivalent to EE and Vodafone (note that Vodafone's numbers are inflated by inclusion of its CWW fixed-line division in the UK). O2 also invested £550m in spectrum in the UK 4G auction (only slightly less than EE) and submitted bids in excess of £1.2bn. [✂] REDACTED.

Figure 10: Capex spending by UK MNOs since beginning of FY 2015



Source: Company financial reports, reproduced from Enders Analysis
Notes: EE, O2, and Vodafone numbers are for the last 6 months ending at the given date. H3G numbers are for the last 6 months ending in June and December. Vodafone does not report separate capex numbers for CWW, so the figures for Vodafone overstate mobile capex expenditures. The average over all 5 periods is shown as a dashed line.

[✂] REDACTED.

This issue can be resolved by the availability of 2.3 GHz and 3.4 GHz spectrum. These bands are highly useful for capacity purposes because they are configured as TDD, thus allowing:

1. the band to be predominantly configured for downlink where the key capacity demands reside; and

2. the use of beam-forming antennas which can both enhance capacity and extend the range of the bands, without needing large numbers of antennas on terminal devices.

[✂] REDACTED. 5G will be an evolution of 4G and is not dependent on allocating very large blocks of spectrum

Historically, new generations of mobile technology have provided significant capacity gains through improved technical efficiency and use of new frequency bands. Within the Consultation, there appears to be an implicit expectation that 5G will be important in enhancing network capacity and that the PSSR award should be crafted to facilitate its emergence. However, in this section, we show that 5G is likely to differ in its form and its method of introduction compared to previous generations: the optimal route to deploying 5G is, almost certainly, via timely availability of new spectrum, including 3.4 GHz, for 4G solutions which can subsequently evolve to 5G. We expect many of the innovations that 5G promises to emerge initially in 4G and evolve to 5G. These include network function virtualisation, Internet of Things (IoT) support and heterogeneous network capability. Hence, 5G benefits can be achieved early, at least in part, through vibrant 4G deployment and evolution.

We also address the view that 5G deployment might need 100 MHz carrier bandwidths. We show that the consumer demand for associated data rates does not yet exist, that the same consumer speeds could be achieved with carrier aggregation of 20 MHz channels, and that equipment to utilise broad channels will not be available until after 2020. We also point out that there are other viable routes to delivering 100 MHz carriers after an auction, such as spectrum sharing or spectrum swaps. Hence, we conclude that the best way to support development of 5G is to prioritise use of PSSR spectrum to alleviate 4G capacity constraints, and policy should not be distorted to accommodate the unrealistic idea that a single carrier might launch an early 5G network using a large block of 3.4 GHz spectrum.

This section is set out in three parts. In Section 5.6, we discuss what form 5G might take, then the process and timeline for its introduction. In Section 5.7, we explore whether broad carriers will be needed and if so how they might materialise. In Section 5.8, we set out the implications of our analysis for spectrum policy, in particular the PSSR award.

5.6. Likely form and evolution of 5G

Although 5G is still in development, there is a general consensus that it will address three areas:

1. Enhanced mobile broadband, providing higher data rates ubiquitously.
2. Massive machine connectivity, enabling IoT to reach its full potential.
3. Highly reliable and low-latency bearers for the most demanding applications.

There is also an expectation that it will initially be focused on three frequency bands:

1. 700 MHz for wide-area coverage.
2. 3.4-3.8 GHz for higher broadband capacity.

3. A mmWave band perhaps between 24-28 GHz (still to be finalised) where ultra-high capacity and ultra-low latency networks can be deployed.

The standards body, 3GPP, has been tasked with prioritising work on enhanced mobile broadband hence it seems likely that this will be the first form of 5G to appear. It is generally expected that this will be deployed in 3.4-3.8 GHz, although there are no reasons why it could not also be deployed in other bands, such as 700 MHz, 2.3 GHz and 2.6 GHz.

It is anticipated that this initial form of 5G will take the form of a new radio interface. This will enable higher mobile data rates through the use of broader bandwidth channels – up to 100 MHz as compared to 20 MHz in 4G. It may also deliver improved spectrum efficiency, although, as discussed in Section 5, gains are currently proving difficult to find.

5G may also herald network enhancements such as improved levels of network function virtualisation (NFV) compared to 4G. These should reduce network costs and facilitate the introduction of new services, but are unlikely to have any impact on capacity. These are being introduced in 4G in current enhancements and hence part of their benefit will be realised prior to 5G deployment.

The working assumption of the 5G community is that there will at some point be a new radio solution termed “new radio” (NR) which will supplement and then replace 4G. 3GPP is still considering the form that NR might take. Most of the contenders are variants of the existing 4G OFDM radio system enhanced with filtering or other modifications. At present it is unclear whether 5G NR will bring sufficiently compelling advances that will in time replace previous generations, or whether it will bring new capabilities which will be deployed alongside 4G, for example ultra-fast data rates to be used as needed.

When NR is deployed, the working assumption within 3GPP is that it will initially be used in non-standalone mode (NSA) where it will work alongside a 4G carrier. Terminals will receive their main connectivity via 4G including all signalling information and may be directed to a 5G NR carrier in order to perform particular tasks, such as downloading information. Such a deployment may use 4G and 5G carriers within the same frequency band. These may be deployed on separate frequencies or may share the same frequencies but be allocated slices of time. [✂] REDACTED.

At some point in the future it is possible that 5G NR might be deployed in standalone mode (SA) where it does not rely on a 4G carrier and it may be granted dedicated resources rather than sharing them. Whether and when this might happen is uncertain.

With respect to timing, as set out in Section 5, the key 5G standard is expected to be Release 15, due in 2018. It is possible that further releases may be needed after this to provide full functionality. Assuming R15 is complete and available in 2018, it typically takes some two years from release availability to fully certified commercial equipment. This is because chipsets need to be designed, devices taken through a test process, revisions made to specifications when the inevitable bugs and ambiguities are found, and then commercial equipment manufactured, tested and sold. At the earliest, network deployment might start in 2020.

It will likely take MNOs up to two years to fully deploy and test such a new solution and to be comfortable with its reliability ready for large-scale commercial launch. It will likely take a similar time for 5G to be deployed within handsets. Hence, we anticipate the start of large-scale commercial 5G deployment in 2022 at the earliest. This would be consistent with the typical 10-year period between generations – 4G underwent large-scale deployment around 2012 and 3G around 2002. It then takes some time before sufficient traffic migrates over to 5G to provide effective capacity relief. How long this might be depends partly on how rapidly handsets are refreshed and also on policies adopted by MNOs, but perhaps another two years might be needed before a significant percentage of the traffic travels over 5G, taking the timeline to 2024. This timetable is laid out in Figure 11.

Figure 11: Plausible timetable for commercial roll-out of 5G services

		Transition Period 1		Transition Period 2		Long Term			
Development Step	**Expected Timeframe**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
5G standard finalised (Release 15)	2018		▨	■	■	■	■	■	■
Commercial Equipment certification process	2019-2020		▨	▨	▨	■	■	■	■
MNO 5G Network Deployment	2021-2022				▨	▨	▨	■	■
5G compatible headsets developed and sold	2021-2022				▨	▨	▨	■	■
Traffic migrates to 5G to provide capacity relief	2024							▨	▨

Source: NERA Economic Consulting

This leads to two important conclusions:

1. 5G will most likely be deployed gradually and in an evolutionary manner rather than in the revolutionary approach adopted for previous generations, with many of the benefits it promises emerging in evolved 4G.

2. 5G is unlikely to provide material capacity relief until around 2024.

Hence, our expectation is that that MNOs will initially deploy 4G solutions in the bands 3.4-3.6 GHz, possibly upgrading them, perhaps via software update, to NSA 4G/5G operation at some point and then potentially to 5G SA operation in due course. Subsequently, the 3.6-3.8 GHz band will presumably be added to handsets and become part of a broader band, although the timeframe for this is uncertain. This timescale and migratory route suggests that making the 3.4-3.6 GHz bands available as soon as possible will both enable 4G to resolve capacity issues in the short term and leave MNOs well-placed to adopt the migratory approach set out above to eventually deliver 5G.

The implications are:

- there would seem no advantage in delaying band availability in order to assist the process of 5G deployment; and

- 5G cannot resolve the short and medium term capacity issues discussed throughout this document.

5.7. Broad channel bandwidth

It has been suggested by some that a key distinguishing feature of 5G would be channel bandwidths much broader than the 20 MHz currently used for LTE. Bandwidths of up to 100 MHz have been suggested.

The only rationale for such broad bandwidth is to deliver higher data rates to subscribers. Broad channels do not improve capacity as the same capacity can be delivered with, for example, five 20 MHz channels as with one 100 MHz channel.

Using carrier aggregation (CA) a subscriber can bond multiple channels. In the timescales envisaged for 5G it is expected that 4G handsets will be available that can bond five 20 MHz channels together, delivering the same data rates as one broader channel. CA carries some penalties such as increased signalling load and increased battery drain so there is a slight preference to not using it.

There is little evidence that the data rates enabled by either CA or broad channels will be needed in the near future. Using 20 MHz carriers enables data rates of 50 Mbits/s to be delivered when channel conditions are good. Surveys suggest that most users do not notice any improvement in their experience when data rates are above about 1 Mbits/s. At this speed, video streaming is satisfactory and web browsing typically limited by other delays in the network, external network or external servers. Only file download can benefit from higher data rates, but this is rarely undertaken by subscribers. Where needed, CA can be used momentarily to deliver fast download of large files and the impact of a short burst of download on batteries is small. Hence, the benefit of broad channels is very limited, with the implication that other factors, such as optimal auction rules or spectrum availability should not be compromised in order to deliver 100 MHz channels.

Further, as set out above, the emergence of a 5G NR is uncertain, and it is possible that equipment able to use broad bands does not appear, is not widely deployed or is substantially delayed.

All of this suggests that spectrum policy should not be set so as to ensure some or all MNOs have access to 100 MHz channels, as this will likely compromise timing, competition policy and other factors.

Should it transpire that 100 MHz channels are of significant importance then a number of routes could be followed to achieve them:

1. *Use of spectrum trading or swaps or other approaches to defragmentation*. The 3.4-3.8 GHz band is 400 MHz wide so in principle it should be possible for all four MNOs to have 100 MHz carriers. This may be compromised by other legacy users of the band and any need to use guard bands to some degree but might still enable all to have, say, 80 MHz carriers, or some to have 100 MHz carriers and some to have perhaps 50 MHz carriers. With the 3.4 GHz band auctioned first, and the 3.6 GHz band likely to be auctioned a few years later, it is quote likely that MNOs will end up

with two or three blocks in different parts of the wider band. If this becomes a barrier to efficient use post-2020, once 5G is launched, the situation could be resolved by the MNOs trading between themselves to achieve a single contiguous allocation each. If there are inefficiencies in the trading process that act to prevent this, Ofcom could facilitate it using some form of "big bang" event to address fragmentation. We understand that O2 would be willing to commit to participate in such an event in good faith with the aim of achieving contiguous allocations for all MNOs.

2. *Access to shared spectrum*. If the 100 MHz channel is primarily for those users requiring very high speed access, and if such users are either relatively rare or only require short bursts of very high speed, then it may be that a single 100 MHz channel is sufficient to deliver this capability across the entire subscriber base. Hence, another possible approach is for Ofcom to reserve a 100 MHz channel in the 3.6-3.8 GHz band that would be available to all MNOs using a similar approach to that adopted, for example, with the DECT guard-bands. Alternatively, if Ofcom allowed it, two or more MNOs could aggregate their own channels to create a single shared 100 MHz carrier. Clearly, this is a more radical approach and would signify a departure in current spectrum practice, but would align well with Ofcom's and the RSPG's stated intent to enhance the opportunities for spectrum sharing.

3. *Use of shared small-cell network*. The shared spectrum option might facilitate a shared network deployment. It has been noted by NIC and others that the economics of dense small-cell deployment in city centres are such that it is difficult for each MNO to build a business case. However, if all MNOs shared one network, deployed either by a neutral third party or collectively by them (as with current network sharing), the economic viability would be improved. This shared network could then use shared or pooled spectrum, even performing temporary consolidation of sub-carriers in time or geography across multiple operators as needed.

4. *Use of other bands*. There is nothing unusual about 3.4-3.8 GHz and broad carriers could equally be deployed in other bands. The key restriction is that most other bands are insufficiently wide to enable this, but it is possible that rearrangement in the 2.6 GHz band and an expanded 2.3 GHz band might enable up to three broad carriers. mmWave bands might also provide a wide carrier option, albeit in longer timescales.

In summary:

- It is difficult to currently envisage why broad carriers of greater than 20 MHz bandwidth might be required.

- The timescales for the availability of network equipment and handsets to use such broad carriers is unclear and might be beyond 2022.

- If a need for broad carriers in the 3.4-3.8 GHz band does materialise there are multiple approaches to changing the existing allocations that could be used to bring them about.

5.8. Implications

The implications of the discussion above are that:

- Many of the benefits promised by 5G will be delivered, at least in part, within evolving 4G standards, so ensuring sufficient capacity on 4G across all four UK operators will enable these gains to be realised at the earliest opportunity.
- Availability of spectrum in the 3.4 GHz band should not be delayed to align with the timescales for 5G.
- Spectrum in these bands should be auctioned as it becomes available and not retained until the entire band is available.
- Policy should not be biased to ensure MNOs are able to acquire broad channels.
- Periodic reviews might be undertaken to assess whether any intervention is needed to enable defragmentation of spectrum holdings.

6. Efficiency and competition assessment

In Section 2, we introduced a framework for assessing the role of spectrum in realising welfare gains for society through its deployment to provide mobile services. Broadly, spectrum has the potential to generate three types of welfare benefits:

- *Static efficiency gains*. Spectrum can be deployed to enhance the quality of service in the provision of existing mobile services. It may also be a more cost effective and practical alternative to investment in physical network infrastructure. Improved quality of service and lower costs generate increased welfare for both consumers and network operators.

- *Dynamic efficiency gains through innovation*. Spectrum may be used by mobile operators to deploy innovative new services that realise a whole new set of welfare benefits over-and-above those realised through existing services. 5G deployment may fit into this category.

- *Dynamic efficiency gains through competition*. The downstream market for mobile services is highly competitive. Competition imposes discipline on operators to deploy spectrum efficiently, invest in quality of service enhancements and pass cost savings on to consumers through lower prices. This competition realises additional welfare benefits for consumers.

The goal in assigning spectrum licences for commercial services should be to ensure that spectrum use generates the greatest benefits to consumers of those services. That means maximising the sum of static and dynamic efficiency benefits.

As we described in Section 2, Ofcom distinguishes between two sources of value in an operator’s business case to acquire spectrum:

1. intrinsic value; and

2. strategic investment value.

Maximising intrinsic value is implicitly linked to maximising static welfare and dynamic innovation benefits (see Sections 6.3 and 6.4). If an operator is bidding for spectrum solely on the basis of intrinsic value, then their bid should be a good proxy for the benefits that their deployment will generate for consumers. As a general observation, operators should be well placed to estimate the value of additional spectrum with respect to the cost and quality of services of existing mobile services, which are the source of static efficiency benefits. Valuations for new services – which are the source of dynamic benefits from innovation – are subject to much greater uncertainty, especially if deployment is still many years away.

Strategic investment value is implicitly linked to anti-competitive advantages and reducing dynamic competition benefits (see Section 6.5). Access to (sufficient) spectrum is a barrier to entry in mobile services. If an operator’s value for spectrum is inflated because it anticipates having greater pricing power and less pressure on costs if it can block rivals from access to spectrum, then its bid will no longer fairly reflect the benefits that its use can deliver for consumers.

Thus, a spectrum auction that simply allocates spectrum to operators that have the highest willingness to pay regardless of the source of value cannot be expected to maximise overall welfare. To avoid such outcomes, regulators typically adopt spectrum caps or other safeguards so as to prevent undesirable outcomes. An efficiency and competition assessment provides the rationale for such measures.

In this section, we present our own efficiency and competition assessment for the spectrum available in the PSSR award. This builds upon frameworks previously adopted by Ofcom.

Our analysis in in five parts:

- In Section 6.1, we identify the linkages between use of the PSSR spectrum and welfare creation. Here, we borrow directly from Ofcom’s June 2012 competition assessment ahead of the UK 4G auction, but update its dimensions to reflect spectrum use in 2017. We identify sufficient data capacity as the critical dimension in driving welfare creation through spectrum use.

- In Section 6.2, we consider the timelines over which we need to assess efficiency and competition effects. We identify three periods for analysis: a first transition period (TP1), from 2017-18, in which 2.3 GHz is the only new usable spectrum; a second transition period (TP2), from 2019-20, when 1400 MHz and 3.4 GHz will be usable, and a longer-term period after 2020 when other bands will become available. The key difference between our analysis and Ofcom’s work is the identification of the second transition period.

- In Section 6.3, we explore the potential for the PSSR spectrum to generate static efficiency benefits by supporting the provision of 4G services to UK consumers. Here, we use a simple valuation model, which focuses on the impact of capacity constraints across these three time periods, to identify how intrinsic valuations and associated welfare benefits may vary across each of the four operators. These values are highly asymmetric between operators, reflecting their very different exposure to capacity constraints. From this analysis, it is possible to identify some obviously undesirable outcomes from a welfare perspective (such as EE or Vodafone acquiring the entire 2.3 GHz spectrum, O2 not acquiring any 2.3 GHz spectrum, or O2 and H3G not acquiring significant additional spectrum). The implication is that Ofcom should give serious thought to remedies that would preclude such outcomes.

- In Section 6.4, we consider whether the PSSR spectrum could also realise additional benefits though supporting the launch of innovative new services under the 5G banner. We think this is possible, but such benefits are unlikely to materialise before 2020, when other spectrum options will be available. We disagree with Ofcom that there is a benefit to allowing every operator to compete for a block of 100 MHz or more at 3.4 GHz. Indeed, given the likelihood that there will ultimately be a converged 4G-5G ecosystem, we identify the possibility that EE could acquire the entire 3.4 GHz band as a potential long-term barrier to the diffusion of innovation benefits across UK consumers.

- In Section 6.5, we consider the role of the PSSR spectrum in shaping the competitive landscape in mobile through each of our time periods. Our analysis is in three parts.

First, we explore the relevant academic literature, which links capacity constraints to a softening of price competition. Second, we identify leading indicators of reduced competition in the UK mobile market, including evidence of market bifurcation and price increases. Third, we extend our valuation model to explore the potential magnitude of strategic value for Vodafone and EE from securing sufficient PSSR spectrum to block O2 and/or H3G from alleviating capacity constraints across our two transition periods. We show that these values are potentially very large and, if crystallised in bids, could lead to highly inefficient award outcomes.

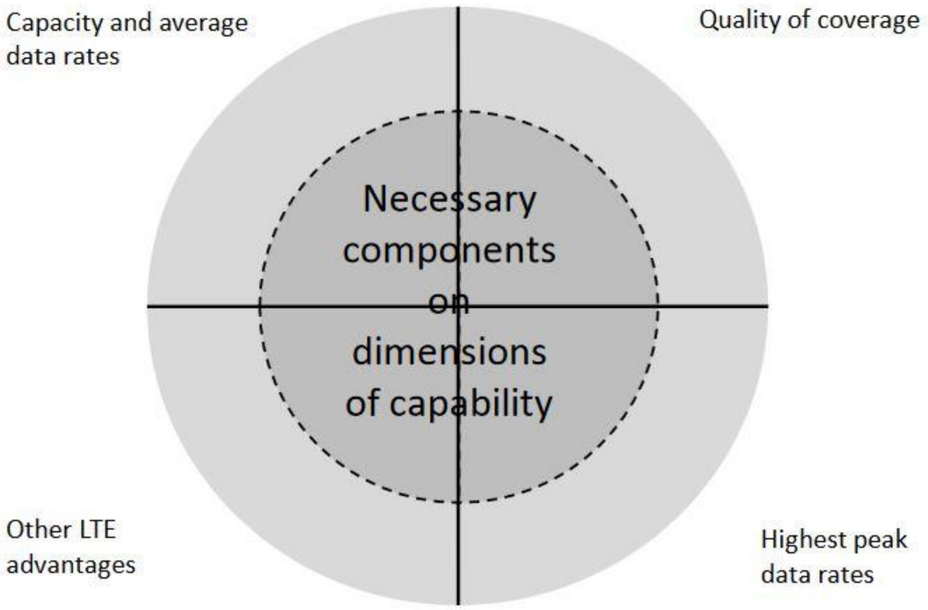
6.1. The dimensions that link spectrum allocation and welfare creation

Ofcom bases its competition assessment for the PSSR auction on an updated version of its June 2012 competition assessment ahead of the UK 4G auction (CD §4.108-4.124). As illustrated in Figure 12, it identified four dimensions along which an operator can deploy spectrum to demonstrate its credibility:

- Capacity and average data rates;
- Quality of coverage;
- Highest peak data rates; and
- Other LTE advantages.

These dimensions not only affect competition in the downstream market; they also generate static welfare benefits for customers of each network, and they may contribute to dynamic efficiency benefits for society through innovation in the use of mobile data.

Figure 12: The dimensions that link spectrum use to efficiency and competition



Source: Figure 4.1 in Ofcom consultation on the “Assessment of future mobile competition and award of 800 MHz and 2.6 GHz”, 24 July 2012.

In its June 2012 competition assessment, Ofcom argued that the dark inner circle represents the necessary minimum requirements. A national wholesaler must have these to be credible, but they may not be sufficient on their own. It further argued that the relevance of these dimensions may change over time. We agree. Below, we present evidence that the ability of operators to provide adequate capacity and average data rates has emerged as the critical component in the ability of operators to offer credible competition and maintain an efficient service for their customers. We place much less weight on “other LTE advantages” – which, we reclassify as "5G readiness"[51] – and "highest peak data rates", where high performance offers marketing benefits for operators but little potential to generate real welfare gains in the next five years.

Coverage is a special case. With respect to the PSSR award, given that only higher frequency bands are available, we see no link between the available spectrum and the ability of operators to provide geographic coverage. Also, all four operators have made significant strides with respect to geographic coverage in recent years. In its competition assessment, Ofcom argues that all operators have at least the minimum spectrum necessary for coverage and that the technical characteristics of the spectrum in the PSSR auction mean that "*it is not an effective means of extending existing levels of mobile coverage*" (CD § 4.111). In surveys, customers do often express dissatisfaction regarding coverage, and this was highlighted in the recent NIC report.[52] However, such concerns primarily relate to the pace at which 4G networks have been rolled out, persistent "not spots" within otherwise covered areas, and poor performance of networks at cell edges. As we discuss below, these problems in large part can all be linked to lack of capacity spectrum, and are best addressed under that heading.

Here, we describe the role of spectrum across the three relevant dimensions in generating welfare benefits for consumers and supporting downstream competition:

1. **4G capacity and average download speeds.** All four UK operators are currently experiencing exceptional growth in demand for 4G data, albeit from different base levels. This places huge pressure on their networks which, realistically, can only be addressed through deploying more spectrum for 4G (see Section 5). Our own model, which is based on forecast data growth of about 50% of the level projected in Ericsson's most recent Mobility Report, [✂] REDACTED.

   Congestion affects the behaviour of operators in multiple ways, all of which result in lower static welfare benefits for customers than would otherwise be the case. Congested networks are unable to maintain quality of service levels for customers, owing to poor latency and lost signals at cell edges. Network operators can also be expected to throttle speeds, so as to share bandwidth across users. Where network densification is not possible, the best alternative is accelerated refarming of 2G and 3G spectrum. However, this is necessarily an iterative process, as spectrum for legacy services must be reduced gradually.

   Of course, customers have the option to switch to other networks. Interestingly, despite evidence that [✂] REDACTED. Whatever the reason, it seems that churn is likely to lag quality of service issues, and – against a background of rapid growth in data use per customer – unlikely to happen fast enough to resolve congestion. The obvious conclusion is that severe spectrum-induced capacity constraints on a network operator will result in significant and enduring losses in static welfare for customers.

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[51] Consistent with §4.114 in Ofcom consultation on "Award of the 2.3 and 3.4 GHz spectrum bands: Competition issues and auction regulations", 24 July 2012.

[52] See pg. 6 of the National Infrastructure Commission report, "Connected Future", 14 December 2016.

Capacity constrained networks can be expected to compete less vigorously for customers and may cease to be credible competitors for customers that place a high value on reliable network performance. This, in turn, may allow unconstrained networks to charge higher prices. In the worst case, a congested network may suffer a consumer backlash that greatly diminishes its brand value and reduces its credibility across the entire market (see discussion of VHA's decline in Section 6.5.1). Such effects may be enduring. Given that customers appear sluggish in moving away from under-performing networks, they can be expected to be equally sluggish in recognising opportunities to return to those networks once performance improves.

2. **Headline speed.** EE currently enjoys a significant advantage over its rivals in terms of the peak speeds that it can provide to customers, owing to its spectrum advantage which enables it to utilise the latest carrier aggregation technology. However, technology constraints on the number of carriers that can be aggregated place a limit on EE's ability to grow its peak speed. In the medium term, with refarming and 1400 MHz, Vodafone is positioned to catch up with EE's high speed offering, regardless of whether either party acquires PSSR spectrum.[53] Furthermore, the amount of PSSR spectrum that O2 and H3G would need to catch up with EE's peak speed is less than their requirements to address 4G capacity issues, so any concerns with respect to peak speed should be solved if the capacity problem is addressed.

   In its marketing, EE puts considerable emphasis on its position as the UK MNO that can provide the "fastest speeds".[54] This implies that peak speed does matter to some extent, and may contribute to a bifurcation of the market. However, EE's peak speed is already well above what consumers need for everyday data use. Furthermore, survey work provided to us by O2 suggests that although consumers say they care about speed, what they really value is consistent performance with low latency, adequate speed and high availability, all factors that relate primarily to network congestion and roll-out, not peak speed. In sum, this suggests that differences in headline speeds do not matter much for static welfare benefits but may have a modest impact on competition.

3. **5G readiness.** 3.4 GHz and 3.6 GHz are identified as potential pioneer bands for launch of 5G services. We concur with this and expect to see 5G deployments in these bands as equipment becomes available. There has been much talk of operators deploying 5G in blocks of contiguous spectrum of up to 100 MHz, to support ultra-fast data. However, we have not identified any evidence from manufacturers to support the notion that such large contiguous blocks are really essential for 5G (see Section 5.7). In practice, we anticipate that such benefits may be largely replicated through a converged 4G/5G ecosystem that takes advantage of carrier aggregation across a range of bands, such as 3.4-3.8 GHz, 2.3 GHz and 2.6 GHz. It is also unlikely that there will be widespread equipment availability for 5G roll out until after 2020,

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[53] We recognise that EE may retain some residual advantage because of its strength in 1800 MHz and 2600 MHz, two of the most widely supported bands for carrier aggregation. PSSR spectrum cannot address this disparity.

[54] See, for example, http://ee.co.uk/why-ee/4g-coverage.

which implies that 5G readiness is unlikely to have any welfare impacts or be a competitive differentiator between networks in the near future.

The Consultation leaves us somewhat confused regarding Ofcom's position on the relative importance of these dimensions. On the one hand, at CD §4.115, Ofcom says that "*for at least the next few years, we consider it is only in terms of capacity and coverage that there are necessary minimum components which an MNO will need to be credible*". This is closely aligned with our analysis. On the other hand, as justification for its choice of competition measures, it cites the possibility that more spectrum may make Vodafone a more effective competitor to EE as justification for placing no restrictions on its ability to bid for 2.3 GHz (CD §5.60) and it prioritises (unrealistic) benefits of 5G readiness over 4G capacity in its choice of remedies for 3.4 GHz (CD §5.74).

Reflecting its primary goal of maintaining four credible MNOs, Ofcom should focus on the capacity problem. The key to maximising efficiency and competition benefits for UK consumers for the foreseeable future is alleviating spectrum-induced capacity constraints. This requires two things to happen. Firstly, Ofcom has to bring the PSSR spectrum to market as soon as possible, and ensure that it is offered in a competitive environment where intrinsic business cases will win out at fair market prices. Second, operators that face congestion challenges will need to step up and buy the spectrum. Reflecting this, in the following sections, our analysis focuses on the efficiency and competition implications of congestion, and how the timeline for availability of PSSR spectrum can affect this.

6.2. Timeframe for analysis

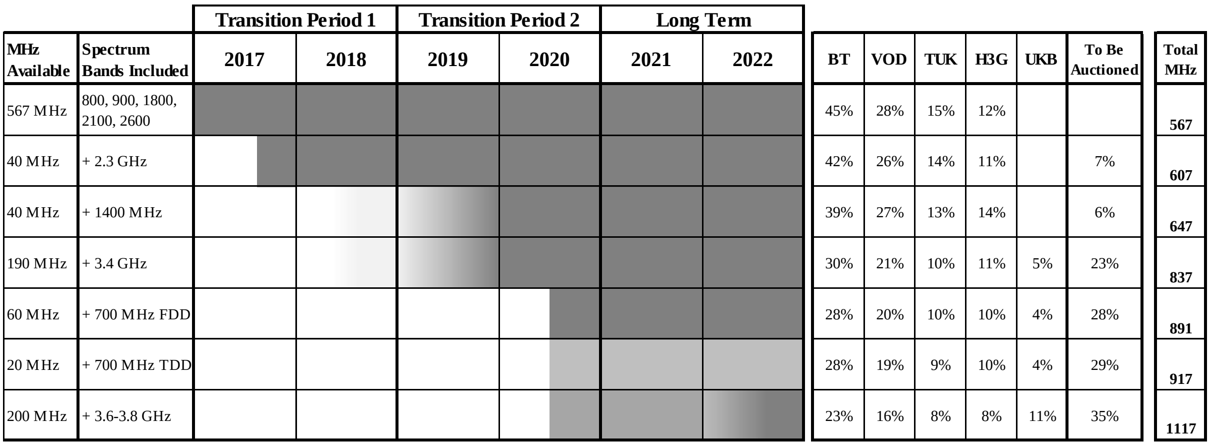
In the Consultation, Ofcom distinguishes between the “transitional period”, and the period afterwards when spectrum availability will be increased (CD §1.29). However, it appears to have missed evidence that there will also be a time gap of two years or more between availability of 3.4 GHz and 3.6 GHz. This is important because the quantity of new spectrum available at 2.3 GHz is almost certainly too small to address data capacity concerns beyond the short term, with the implication that 3.4 GHz will become an essential resource for adding incremental 4G capacity from 2019. Indeed, the 3.4 GHz band is likely to be more important for provision of 4G services in the UK than in other European markets because two operators have unusually weak spectrum holdings across other frequency bands, and thus lack alternatives to add capacity.

Accordingly, our analysis focuses on three time periods, as illustrated in Figure 13:

- The first transitional period (TP1): from now until early/mid 2019, during which the only new usable spectrum will be the 40 MHz at 2.3 GHz.
- The second transitional period (TP2): the period from 2019 until mid-2020 or later, during which 1400 MHz and 3.4 GHz spectrum will become usable for 4G services.
- The long-term: the period beyond 2020, at which point further spectrum at 700 MHz and 3.6 GHz should become available, for 4G and 5G.

These are not short periods from the perspective of managing a rapid increase in traffic on a congested network.

Figure 13: UK spectrum availability for mobile services, 2017-2022



MHz Available	Spectrum Bands Included	BT	VOD	TUK	H3G	UKB	To Be Auctioned	Total MHz
567 MHz	800, 900, 1800, 2100, 2600	45%	28%	15%	12%			567
40 MHz	+ 2.3 GHz	42%	26%	14%	11%		7%	607
40 MHz	+ 1400 MHz	39%	27%	13%	14%		6%	647
190 MHz	+ 3.4 GHz	30%	21%	10%	11%	5%	23%	837
60 MHz	+ 700 MHz FDD	28%	20%	10%	10%	4%	28%	891
20 MHz	+ 700 MHz TDD	28%	19%	9%	10%	4%	29%	917
200 MHz	+ 3.6-3.8 GHz	23%	16%	8%	8%	11%	35%	1117

Source: NERA Economic Consulting adapted from Ofcom Figure 4.2 at CD §4.43.
Notes: Handsets incorporating 1400 MHz and 3.4 GHz are expected to become widely available from mid-2018, with the ecosystem reaching maturity in 2019. Ecosystem for 700 MHz FDD spectrum is expected to be fully mature as soon as band clearance is complete, estimated to be in 2020. Ecosystem for 700 MHz TDD is not established, and usefulness is uncertain, but could be available in 2020 at the earliest. Ecosystem for 3600 MHz may be fully mature by 2020, but wide areas of the UK may be sterilised by legacy fixed link use until around 2022.

This figure is an amended version of Ofcom’s spectrum availability chart at CD §4.43. The main changes from the Ofcom chart are as follows:

- Based on conversations with vendors, O2 tell us they expect handsets incorporating 1400 MHz and 3.4 GHz to become widely available from mid-2018, with the ecosystem reaching maturity in 2019. Accordingly, our grey shading for 2019 is darker than in Ofcom’s chart, so as to make it clear that 3.4 GHz can start playing a substantive role in alleviating 4G congestion in urban areas from 2019.

- We assume 3.6 GHz will not be available and usable until mid-2020. We expect this band to be used for converged 4G-5G services, but there is uncertainty when it will be integrated fully into handsets. We expect this band to play a role in alleviating capacity from around 2020, with some risk of further delay, not 2018/19, as implied in Ofcom’s chart. Ofcom has also indicated that clearance of fixed links from the band may not happen before mid-2022[55], which would prevent mobile roll-out in many areas of the country, including Central & West London.

Ofcom’s omission of the second transition period in its analysis explains its failure to recognise the importance of the 3.4 GHz band to O2 and H3G as a critical source of 4G capacity. As we will show below, failure to acquire a critical mass of this spectrum (in addition to 2.3 GHz) would [✂] REDACTED.

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[55] Ofcom, Improving consumer access to mobile services at 3.6 to 3.8 GHz, 6 October 2016.

6.3. Static efficiency and associated welfare benefits

The PSSR spectrum has the potential to play a significant role in supporting expanded welfare generation as more and more mobile customers consume ever greater amounts of data over 4G networks. We argue here that the key to maximising this benefit is allocation of additional spectrum to networks at or approaching capacity constraints. If spectrum is instead allocated to networks that have abundant capacity, then welfare generation will be curtailed. The ability of customers to switch between networks provides a floor on the potential for static efficiency losses. Nevertheless, as customer switching is likely to lag capacity problems, we show that consumer welfare losses in the order of £5.3 billion within the next four years are conceivable if O2 and H3G do not secure sufficient spectrum at 2.3 GHz and 3.4 GHz.

The timing of access to spectrum is crucial. In TP1, only 2.3 GHz has potential to address capacity issues. However, the available spectrum at 2.3 GHz is only 40 MHz and may be split across two or more operators. Accordingly, constrained operators will also need to acquire 3.4 GHz for 4G capacity, so as to avoid a further capacity crunch in TP2. Other spectrum bands, such as 700 MHz and 3.6 GHz can alleviate capacity problems after 2020, but will arrive too late to provide an alternative during the transition periods.

In particular, our analysis shows that an efficient outcome requires O2 and H3G to acquire significant amounts of spectrum. Importantly, these two operators each require spectrum in both the 2.3 GHz and 3.4 GHz bands, [✂] REDACTED.

This analysis should not be confused as a plea for spectrum to be reserved or allocated on the cheap to constrained networks, so as to protect their market share. Ofcom is appropriately agnostic about shifts in customers across networks, provided all operators remain credible competitors, and it is the responsibility of each network operator to invest adequately in their networks. If competing on a level playing field, we would expect the obvious high incremental values for additional spectrum for O2 and H3G to translate into winning bids in the PSSR auction. Rather, this analysis highlights the potential for large welfare losses if such outcomes do not materialise. They provide a strong rationale for remedies to preclude obviously bad outcomes in which EE and/or Vodafone, for whatever reason, bid to monopolise the new spectrum, in either band.

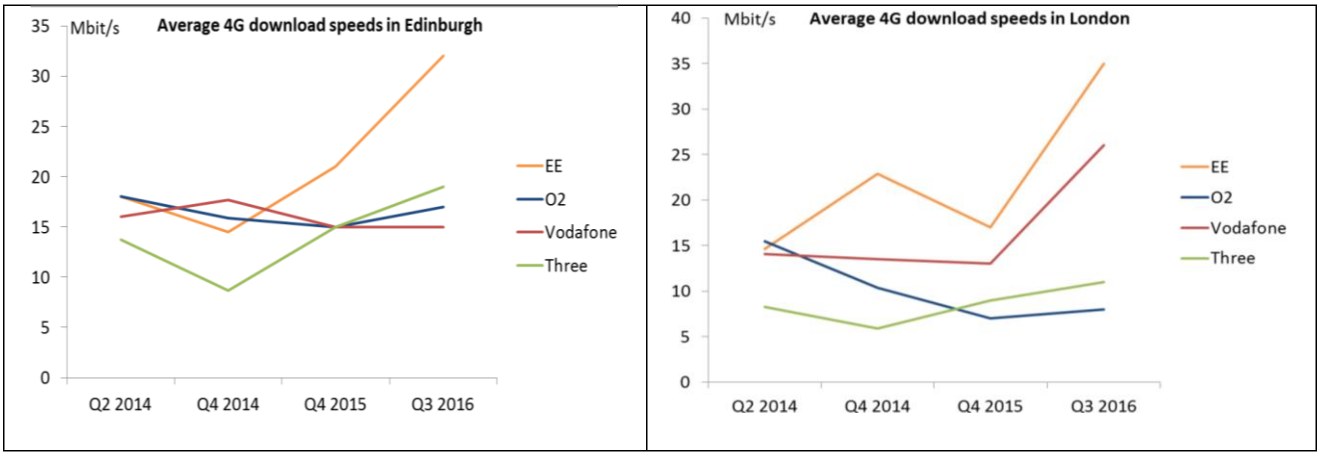
The remainder of our analysis of static efficiency issues is split into three parts. In Section 6.3.1, we describe the current situation, [✂] REDACTED. In Section 6.3.2, we present the results of our valuation model, which compares the intrinsic value of incremental PSSR spectrum across the four operators. This highlights the obvious efficiency benefits of O2 and H3G securing the lion’s share of new spectrum to support 4G capacity, including the entire 2.3 GHz band. In Section 6.3.3, we extend our valuation model to estimate the welfare losses for UK consumers, owing to reduced quality of service and enforced switching costs, which may result from a failure of O2 and H3G to secure the spectrum they need [✂] REDACTED.

6.3.1. The current situation

In Sections 3 and 4, we presented evidence that the assignment of spectrum in the UK is unusually asymmetric across operators, and that there was no basis to believe that this was the result of efficient market processes. Indeed, it should be obvious to any impartial observer that the current assignment of spectrum is inefficient: while two operators are warehousing spectrum, two others are close to full capacity and their customers are starting to suffer as a result. [✂] REDACTED. We link these problems directly to lack of spectrum.

Ofcom publishes recurring assessments of the quality of mobile networks in the UK.[56] Figure 14 plots average 4G download speeds as measured in Ofcom's four assessments to date in two locations, Edinburgh and London. We consider 4G download speeds to be a good proxy for the quality and spare capacity of the network.

Figure 14: Average speeds in Edinburgh and London



Source: Data from Ofcom reports, "Measuring mobile broadband performance in the UK", 2 April 2015 and "Smartphone Cities", 31 March 2016 and 16 December 2016.

The differences in performance of the networks across the cities is consistent with our concerns regarding access to capacity spectrum:

- In both locations, EE is leading the pack and has recently pulled away in terms of average speed in both locations. This is owing to EE being able to deploy full 20 MHz LTE carriers as well as having a lightly loaded network.
- Vodafone has sufficient spectrum and idle capacity to match EE's network quality, as illustrated by its improved performance in London. It may not yet be able to generate the highest speeds available on the EE network, but its average speeds are clearly sufficient to meet the needs of its user base.
- O2 has [✂] REDACTED.
- H3G has recently caught up with O2, but does not have access to the bandwidth to match EE's or Vodafone's average speeds in London. [✂] REDACTED. Its average speed in London is noticeably slower than it is in Edinburgh.

Figure 15, which compares the proportion of 4G download tests over 2Mbit/s, by city and MNO, tells a similar story. In Edinburgh, O2 has achieved a 97% standard, equivalent to the

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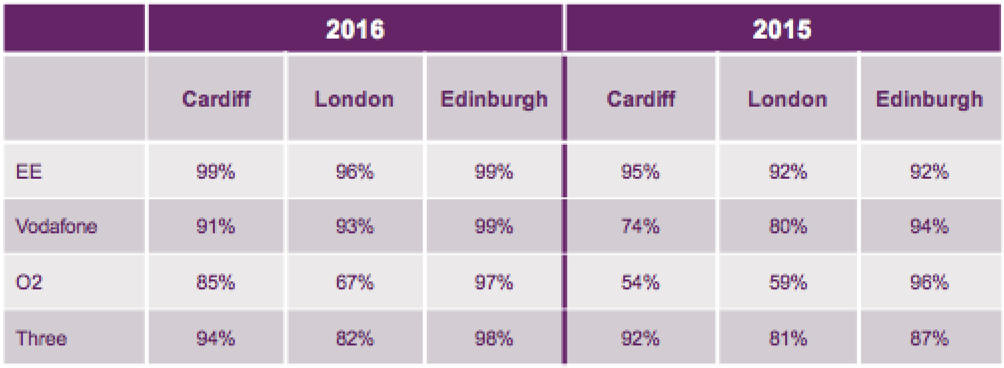
[56] The latest report titled "Smartphone Cities: Measuring 4G mobile broadband and voice performance" can be found at https://www.ofcom.org.uk/research-and-data/broadband-research/smartphone-cities/smartphone-cities-dec16.

other operators. Between 2015 and 2016, it greatly improved its performance in Cardiff, where it was lagging its rivals. However, in London, O2 only marginally improved its performance between 2015 and 2016, while EE and Vodafone are very strong. We note also that whereas H3G has improved performance in Edinburgh and Cardiff to levels comparable with EE and Vodafone, it has not been able to improve in London.

Figure 15: Proportion of 4G download tests over 2Mbit/s, by city and MNO: 2015 vs. 2016



	2016			2015		
	Cardiff	London	Edinburgh	Cardiff	London	Edinburgh
EE	99%	96%	99%	95%	92%	92%
Vodafone	91%	93%	99%	74%	80%	94%
O2	85%	67%	97%	54%	59%	96%
Three	94%	82%	98%	92%	81%	87%

Source: Ofcom "Smartphone Cities Report", December 2016.

In summary, recent trends indicate that:

- EE can achieve the highest average speeds as it has access to full 20 MHz LTE carriers and at the same time has sufficient spare capacity.
- Vodafone already has sufficient spectrum to match EE's network experience. Although it cannot yet offer the very highest speeds possible on the EE network, it is not obvious that this matters much from a customer perspective.
- O2 and H3G appear to have reached a natural limit in terms of user experience that they can provide in non-congested areas (between 15 to 20 Mbit/s) without additional spectrum.
- [✂] REDACTED.
- [✂] REDACTED.

These divergences in performance cannot be explained by differences in investment. As we reported in Section 5.5, there is no evidence to suggest that O2 has under-invested in its network relative to the other operators. [✂] REDACTED.[57] Indeed, from a commercial perspective, it is difficult to believe it would be a sensible strategy to under-invest in London relative to other cities, given that the London market is such an important proportion of the national market. We conclude that binding constraints created by lack of spectrum for 4G capacity is the explanation for these emerging differences in performance.

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[57] [✂] REDACTED.

[✂] REDACTED.

6.3.2. Modelling the intrinsic value to operators from PSSR award outcomes

To support our analysis, NERA has developed a high-level valuation model which estimates the value of additional spectrum to each of the four MNOs. The data we present below is obviously sensitive, given that we are forecasting an auction that has not yet happened, and we are producing this report on behalf of an operator that plans to bid in the auction. Accordingly, we were tasked by O2 to develop our own model (which is separate from the model that O2 is developing to support its bidding strategy), using a format that Ofcom could potentially replicate using public domain data. **It is designed to support high-level inferences on the efficiency, competition and welfare impact of particular outcomes to the PSSR auction, not as a tool to forecast actual bids in the auction.**

Our model is a “subscriber loss avoidance model”. It uses reasonable assumptions about traffic growth and spectrum availability for each of the networks to model capacity constraints over time. We have made further assumptions about how spectrum-induced capacity constraints could drive churn of customers from congested to uncongested networks. We also consider the impact of some networks being able to offer higher peak speeds.

We deliberately have not attempted to develop a detailed cost model, for two reasons. First, such models are complex to develop and subject to many detailed assumptions. We see no merit in attempting such an exercise in the time available for decisions on the PSSR award. Second, and more importantly, we believe that spectrum asymmetry has reached a point at which it turns conventional valuation models on their head: operators with limited spectrum have few costs they can avoid from acquiring more spectrum because they lack the frequencies they need to take full advantage of network improvements; and operators with large spectrum holdings have no near-term costs that they need to avoid. As a result, commercial value associated with avoiding market share losses or making gains at expense of congested rivals become the dominant factor in valuation models.

We recognise that there are sources of value that our model does not capture, such as the propagation differences between 2.3 GHz and 3.4 GHz, the marketing benefits from being able to provide higher peak speeds, and the “option value” of having additional reserves of spectrum, so as to support expansion in response to competitive success, unexpectedly strong demand growth or launch of 5G services. We consider that these sources of value are second order relative to congestion and, anyway, will likely trend with values attached to avoiding congestion. We do consider these other factors in our qualitative analysis of the model results below and throughout this report.

One implication of this new reality is that the boundary between intrinsic value and strategic investment value is somewhat blurred. In our analysis, we categorise intrinsic value as including the benefits from avoiding customer loss owing to congestion, and strategic investment value as the benefits from customer gains which result from operators with uncongested networks acquiring spectrum that blocks rivals from alleviating congestion. There is obviously some ambiguity with respect to where intrinsic value ends and strategic investment value starts. For example, to some extent, all operators – and especially those with lower market shares – may have legitimate expectations that they can grow their market share based on their intrinsic competitive proposition. To avoid over-complicating our model, we make the simplifying assumption that market shares will remain static if all operators avoid capacity constraints. We recognise that this assumption may be harsher on H3G and Vodafone, than on O2 and EE, given the former two have in recent years under-performed in attracting new customers.

Key assumptions

A full description of the model is provided in Annex II. Here, we briefly highlight the key assumptions:

- **Data demand growth.** Our assumptions for growth in data demand were set out in Section 5.1 and Figure 8. Our assumptions are roughly in line with Ofcom's own estimates up to 2023. Beyond that, we assume lower growth. We believe that our assumptions are conservative relative to many industry forecasts.

  Average data consumption per customer currently varies significantly across networks, from around 0.9 GB per month for Vodafone and O2, up to 4.2 GB per month for H3G.[58] Projecting forward, we assume that average data rates across networks will converge, as customers on other networks catch up with early adopters on H3G's network. There is already some evidence for this, as the most recent data highlights faster growth in data use on the networks of EE, O2 and Vodafone than on H3G's network. Nevertheless, we assume some disparity will remain by 2026, as set out in **Error! Reference source not found.**.

- **Churn rates.** In our model, we assume that congested networks will experience higher churn rates. We estimate capacity on all four networks over time based on the spectrum that is usable and compare that to the expected data traffic on each network.[59] If data traffic exceeds the available capacity, we assume that some customers move away from their network to networks with spare capacity. Specifically, we identify a pool of customers that would need to leave the network to remove congestion, and assume that 20% of this pool switch away each year. We think this is a conservative assumption; for example, it is smaller than the two percentage point per annum drop in market share experienced by Vodafone-Hutchison Australia (VHA) between 2011 and 2014 following network and branding problems, as described in Section 6.5.1.

- **Asymmetric ARPUs.** We assume that average ARPUs for operators remain at their 2016 levels. Specifically, we assume ARPUs of £18.35 (EE), £19.30 (H3G), £14.25

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[58] Data based on company reports and subscriber data supplied by O2 from Q2 2016 (the last non-estimated values). MVNO customers are included to estimate the total capacity on a network.

[59] In our model, we assume: 2.3 GHz spectrum can be used immediately; 3.4 GHz spectrum can be partially used (50%) by 2019 and fully used (100%) by 2020; 1400 MHz will be useable from 2019; and 700 MHz and 3.6 GHz will be useable by 2021. We also make reasonable assumptions about ability of operators to refarm spectrum from 2G and 3G use.

(O2); and £16.41 (Vodafone).[60] O2's ARPUs are lower because it has a high proportion of lower value MVNO subscribers on its network.

- **Symmetric cash flow margin assumption.** We assume that 20% of ARPU is retained as contribution to fixed costs and profits whereas the rest is spent on customer-related costs.[61]

Vulnerability of UK operators to capacity constraints

In [✂] REDACTED.

, we plot the ability of each UK network to meet capacity over time in the case they do not receive any new spectrum. The quality of each network in absolute terms (average download speeds, latency etc.) depends on today's spectrum holdings, so absolute network quality across networks at the same % of network quality may differ.[62] The model assumes that a congested network would lose market share to operators that have spare capacity, as per the above assumptions. In this chart, each operator is modelled independently, so we are implicitly assuming in each case that at least two other networks are not capacity constrained. As can be seen, [✂] REDACTED, while EE and Vodafone would not experience any issues before 2020. H3G's outlook is better than O2, as it has 1400 MHz spectrum which will be usable from 2019. Network quality levels off towards 2026, owing to the combined effects of slowing growth in data usage and loss of subscribers to other networks. This graph is purely for illustrative purposes, as in practice we expect the release of PSSR spectrum to alleviate these constraints for some or all operators.

[✂] REDACTED.

In [✂] REDACTED, we map the impact of such losses of subscribers on cash flows. The lost cash flow places a ceiling on the value that each operator should be willing to invest in PSSR spectrum to address capacity constraints during the relevant time periods.

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[60] Data supplied by O2. ARPU is a weighted average of the ARPU from MNO and MVNO customers.

[61] This is consistent with EBITDA margins reported by O2 (27%), Vodafone (19%), EE (20%) and H3G (33%) for 2016.

[62] For example, EE can achieve much higher average data speeds than O2, as it has carriers whereas O2 does not. We also note that, according to [✂] REDACTED.

, O2's network quality % is higher than H3G's until 2018 even though Ofcom's Smartphone Cities report (December 2016) suggests that H3G's network is slightly better in absolute terms in some urban areas. These local differences may be owing to a number of factors, such as the actual frequencies deployed for 4G, location of cell sites and congestion in specific areas.

[✂] REDACTED.

Considering each operator in turn, the model reveals the following:

EE

- EE has sufficient spectrum to meet projected demand through TP1. Given constraints on carrier aggregation, it also already has sufficient spectrum to provide maximum data rates through to 2021. Accordingly, it is unlikely to have any intrinsic value for additional spectrum in TP1.
- EE also has sufficient spectrum to meet projected demand through TP2. However, owing to its large customer base and their relatively high data use rates, it may plausibly approach capacity around 2020, especially if it prefers not to accelerate refarming. Accordingly, it is likely to place some modest intrinsic value on additional 4G data capacity in TP2. This could be addressed with as little as 10 MHz of 3.4 GHz spectrum, and would not require 2.3 GHz spectrum.
- Beyond 2020, EE will need to expand 4G/5G capacity. This could be met through future spectrum releases, such as 700 MHz and 3.6 GHz, so anticipated auction outcomes for these bands should place a ceiling on incremental willingness to pay (absent strategic investment value) for 2.3 GHz or 3.4 GHz.

Vodafone

- Vodafone has sufficient spectrum to meet projected demand through TP1. However, it lags EE in its ability to offer the highest speeds. Acquiring 20 MHz at 2.3 GHz may allow Vodafone to address this issue, by enabling it to deploy higher order carrier aggregation, subject to CA equipment availability. Therefore, even though our model indicates it does not need 2.3 GHz for capacity, it may place some modest intrinsic value on this spectrum relative to other bands.
- Vodafone also has sufficient spectrum to meet projected demand through TP2, especially as 1400 MHz will become usable. Despite having less spectrum than EE, it is potentially less constrained, owing to its modest customer base and relatively low data use rates per customer. Vodafone would need to have a very bullish projection for its ability to gain market share over the next four years for it to have any need for more spectrum in TP1 or TP2. At the most, Vodafone may place some modest intrinsic value on additional 4G data capacity in TP2.
- Beyond 2020, like EE, Vodafone will need to expand 4G/5G capacity. This demand could be met through future spectrum releases, such as 700 MHz and 3.6 GHz, so anticipated auction outcomes for these bands should place a ceiling on incremental willingness to pay (absent strategic investment value) for 2.3 GHz or 3.4 GHz.

O2

[✂] REDACTED.

H3G

- In TP1, H3G faces a capacity challenge owing to its user base having very high data use rates. This could be addressed with 20 MHz of 2.3 GHz spectrum. H3G has a much smaller customer base than O2, so has less to lose in absolute cash flow terms. H3G also has the option to throttle traffic in congested areas from the very high levels of data usage they currently experience on their network to a level more in line with the industry average. [✂] REDACTED.

- In TP2, H3G’s 1400 MHz spectrum will become usable, thus substantially easing its congestion issues. Furthermore, we anticipate that its user base will see less rapid growth in data usage than other networks, as the market for 4G data is maturing and its customer base is skewed towards early adopters of mobile data. The model predicts that H3G will place a premium on acquiring 20 MHz of spectrum in the 3.4 GHz band for 4G deployment, so as to maintain capacity through 2020.

- As with other operators, any additional demand beyond the above could potentially be met by 700 MHz and 3.6 GHz.

Cumulative and marginal values of 10 MHz blocks for 4G capacity to UK operators

In [✂] REDACTED.

, we show the cumulative value to each operator of adding 10 MHz blocks for 4G capacity. As we are only considering capacity, we make no differentiation here between the type of spectrum by band. However, for each block, we identify the proportion of value associated with being able to add spectrum in a particular time period.

Specifically, we distinguish four categories of value:

- 20 MHz in TP1: Value of having additional capacity up to 20 MHz in TP1 (2017-18), which could only be met with 2.3 GHz spectrum. Only O2 and H3G have value in this category.

- 40 MHz in TP1: Value of having additional capacity between 20 MHz and 40 MHz in TP1, which could only be met with 2.3 GHz spectrum. Only O2 and H3G have a value in this category but this is small.

- TP2 value: Value of having additional capacity in TP2 (2019-20), which could be met with 2.3 GHz or 3.4 GHz spectrum. Again, only O2 and H3G have value in this category.

- Long-term value: Value of having additional capacity in the longer term (beyond 2020) which could be met with PSSR spectrum or future releases, most likely 3.6 GHz or 700 MHz. All operators have value in this category.

[✂] REDACTED.

We draw the following inferences from these results:

- Based on intrinsic capacity value, only O2 and H3G have an intrinsic premium for acquiring 2.3 GHz spectrum over other bands. Given that there is plenty of other spectrum that will be usable later, the implication is that measures that prevent EE and Vodafone bidding for this spectrum would not impose any risk to allocative efficiency.

- Based on intrinsic capacity value, only O2 and H3G have an intrinsic premium for acquiring 3.4 GHz spectrum over other bands. Given that there is plenty of other spectrum coming after 2020, the implication is that measures that substantially constrain EE's and Vodafone's ability to bid for this band would also not impose any risk to allocative efficiency.

- Notwithstanding these points, EE's value for incremental spectrum in the long term is substantial, assuming it maintains its high market share. If it leverages this long-term value to bid for PSSR spectrum instead of waiting for future releases, it would be a strong contender for PSSR spectrum even without considering strategic value.

- Vodafone has no business case for acquiring substantial amounts of PSSR spectrum. The model implies that its intrinsic value for additional spectrum is low. This reflects Vodafone's large spectrum holdings but comparatively low market share and low average data use per subscriber. In practice, we would expect Vodafone to be a more aggressive bidder than the model suggests, both because it may plausibly hope to recover market share that it has lost over the last seven years, and because the company has a track record across Europe of investing heavily in spectrum. To test the sensitivity of the model on this point, we re-ran the model for Vodafone assuming anticipating intrinsic growth[63] of 0.5 market share points per annum (i.e. 5 percentage points of market share over 10 years). [✂] REDACTED

Our model is based on assumptions about data growth and market churn which may be conservative. Changing these assumptions would have the following impact:

- **Faster data growth**. Our model predicts average monthly data demand of 14 GB by 2026. Increasing this to 18 GB[64] leads to congestion on EE's network by the end of TP2. [✂] REDACTED. The increase in data traffic leaves O2's and H3G's valuations for 2.3 GHz largely unaffected as the impact of additional demand is manly felt in TP2 and the long term. [✂] REDACTED. This is because we assume that H3G will continue to maintain a base of subscribers with higher data consumption than other networks.

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[63] This would be growth owing to normal competition, as opposed to winning market share solely because other operators have spectrum-induced capacity constraints and cannot compete fully.

[64] H3G customers are projected to consume 23 GB, EE customers 18.7 GB, O2 customers 17 GB and Vodafone customers 16.6 GB in 2026.

- **Higher churn rates for capacity constrained operators**. We assume that only 20% of customers whose demand cannot be met by their current network churn away. Increasing this churn rate to 50% raises H3G's valuation for 20 MHz in 2.3 GHz by 35% and O2's by 45%. H3G's valuation for 3.4 GHz spectrum (assuming it can get access to 2.3 GHz) would increase by 10% whereas O2's would increase by 60%.

The **timing of availability of bands** also has a big impact on the model results, in particular with regards to the 2.3 GHz band. If the 2.3 GHz band is made available in 2018 rather than 2017, H3G's value for 20 MHz of 2.3 GHz spectrum will reduce by more than 30% whereas O2's would fall by 5%. Further, H3G's valuation for 3.4 GHz spectrum (assuming it can get access to 20 MHz of 2.3 GHz spectrum) would fall by almost 25%.

Efficient allocation of 2.3 GHz

In [✂] REDACTED, we plot the marginal values of each operator for their first four lots of 10 MHz in rank order (four lots of 10 MHz corresponds to the 40 MHz available at 2.3 GHz). If no other spectrum was available and these were bids in an open auction, the highest four bids (on the left) would be the winners, and the fifth highest bid would set the price.

For each incremental value, we identify the proportion of that value that is dependent on securing spectrum in the Transition Period 1 (2017-18) with dark shading. The value in light shading could be secured using alternative spectrum, such as 3.4 GHz. If we compare only the values in dark shading, this is likely the best proxy for actual efficient allocation of 2.3 GHz spectrum, given other values can be satisfied elsewhere.

In this case, it is [✂] REDACTED.

[✂] REDACTED.

Efficient allocation of 3.4 GHz

In [✂] REDACTED, we plot the marginal values of each operator for their next 15 lots of 10 MHz in rank order (this corresponds to the 150 MHz available at 3.4 GHz).[65] To simplify our analysis, we assume that O2 and H3G each win 20 MHz at 2.3 GHz, whereas Vodafone and EE win no spectrum in these bands.

If no other spectrum was available and these were bids in an open auction, the highest 15 bids (on the left) would be the winners, and the 16th highest bid would set the price.

For each incremental value, we identify the proportion of that value that is dependent on securing spectrum in TP2 (2019-20) with dark shading. The value in light shading could alternatively be secured using alternative spectrum, such as 3.6 GHz. Values in dark shading should be given greater weight when predicting the efficient allocation of 3.4 GHz spectrum, given the light shaded values could be otherwise satisfied.

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[65] To simplify our analysis, we use 10 MHz blocks, rather than the 5 MHz blocks that will actually be available. This does not affect our conclusions. We note that some operators have zero marginal value for very large amounts of spectrum. We have omitted marginal values below £15 million.

[✂] REDACTED.

The model suggests that it is very important for efficiency that O2 win at least [✂] REDACTED and that H3G wins at least [✂] REDACTED. Beyond this point, the amount of value dependent on 3.4 GHz is smaller, and it does not matter so much how the remaining [✂] REDACTED is split across the four operators as long as all four operators have access to additional spectrum usable from 2021.

6.3.3. Modeling the welfare impact of PSSR award outcomes

Building on our valuation analysis, we set out here a high-level welfare loss model that aims to provide an order of magnitude assessment of the welfare losses from “forced churn” if O2 and H3G fail to win sufficient spectrum to alleviate their capacity constraints. The model uses the same assumptions regarding the pace of churn in response to capacity-induced quality of service issues as our valuation analysis. In addition, it assumes that other networks will pick up these lost subscribers which, in turn, may lead to congestion on their networks.

We identify the following sources of welfare loss:

1. **Switch costs.** We estimate the switch costs for customers churning away from congested networks. Our model is based on the switch costs identified in Ofcom’s Mobile Switching Quantitative Research.[66] Overall, switch costs are only a small fraction of overall welfare losses.[67] They include:

    - **Search costs**. Ofcom state that 80% of all switchers compared providers and researched what they needed to do in order to switch. Assuming that each of these activities takes no more than 2 hours and using the UK minimum wage as a lower bound on opportunity cost (£6.70), we can determine a conservative estimate of these search costs.

    - **Other transaction costs**. Ofcom list five additional activities undertaken by switchers.[68] Assuming that each of these activities takes no more than 1 hour and using the UK minimum wage as a lower bound on opportunity cost (£6.70), we can determine a conservative estimate of these transaction costs.

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[66] Ofcom, Mobile Switching Quantitative Research, 12 September 2016.

[67] We understand that Ofcom is currently working on reducing switch costs, so some of these costs may be reduced in the future. This would not significantly impact our results as most welfare losses are incurred by customers who remain on congested networks and suffer from lower network quality.

[68] Ibid, slide 31: “Choose the date you wanted to start using your new mobile provider” – 61%, “Need to set up a new online account” – 60%, Experience your old provide trying to persuade you to stay” – 51%, “Unlock your handset to take it with you” – 30%, “move content from one cloud storage to another” – 28%.

    - **Termination charges**. Based on Ofcom's research, we estimate that, on average, switchers paid £5.00 to their previous operator in early termination charges.[69]

    - **Contract overlap**. Ofcom state that 19% of switchers experienced an unwanted contract overlap of an average of 13.2 days. We use ARPU of £16.70 to estimate the additional costs from unwanted contract overlap.

    - **Lost consumer welfare owing to temporary loss of service**. Around 20% of all switchers experienced temporary loss of service. Assuming that customers value their mobile data plan at £90 per month[70] and assuming loss of service for one day on average for these customers, we can quantify the welfare losses owing to temporary loss of service.

2. **Reduction in network quality.** Our model assumes that the pace of switching is insufficient to address congestion [✂] REDACTED owing to contract length, customer inertia and other factors. Accordingly, customers that continue to use these networks in areas where macrocells are congested will receive a declining quality of service. This will translate into a loss of welfare. We assume that willingness to pay for mobile data is £31.40 per month and that network congestion will only affect customers living in urban areas.[71] Assuming that a reduction in network quality reduces consumer surplus proportionately, we estimate the annual welfare loss to all UK customers.[72]

3. **Value of other O2 services.** We have not attempted to quantify the value that subscribers may place on other aspects of O2's services that they would lose if they move to another network. Given O2's success in adding and sustaining market share in recent years, despite its capacity challenges, this value may be substantial.

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[69] Ibid, slide 52: Ofcom state that on average 27% of all customers who switched gave notice before the end of their contract. 37% of these customers paid early termination charges. A detailed breakdown of costs paid is also provided on slide 52. If we assume that termination charges were no higher than £150, Ofcom's research suggests that these customers paid on average £4.80. As only 10% of customers incurred termination charges, this amounts to £0.48 per switching customer.

[70] This is based on a 2013 study of willingness to pay for mobile services by Plum Consulting. Plum estimate that the willingness to pay for 4G services in the EU is around Euro 1,262 per annum. Plum ,2013, Valuing the use of spectrum in the EU – An independent assessment for the GSMA, http://www.gsma.com/spectrum/wp-content/uploads/2013/06/Economic-Value-of-Spectrum-Use-in-Europe_Junev4.1.pdf

[71] We use the population share living in built-up areas with more than 200,000 inhabitants as a proxy. This is around 49% of the UK population.

[72] Network quality is measured as ln(quality)= max(1,capacity/demand – 1). Note that absolute network quality may differ across networks. We assume that consumers have self-selected their preferred network based on capability, coverage, customer services and price. We further assume that the willingness to pay is the same across customers for their preferred network. The welfare losses are only incurred by O2 and H3G customers living in urban areas in TP1, TP2 and 2021-2022, as EE and Vodafone remain unconstrained in all of these scenarios even after absorbing all of these new customers. So, effectively, we are assuming that O2 and H3G customers value their current connection at £31.40 per month, but that value deteriorates proportionately with network quality. This is a conservative estimate of welfare loss as it does not include additional losses owing to switching to a second-best option which provides lower consumer surplus based on capability and price.

We set out below and in Table 4 our indicative estimates for discounted welfare losses under scenarios for allocation of PSSR spectrum in TP1 and TP2.[73] We do not consider welfare effects beyond 2020 as these become increasingly uncertain owing to the potential for further spectrum releases, for example in the form of shared or unlicensed spectrum.

We consider four scenarios where we optimise allocation of spectrum to minimise welfare loss, subject to the constraints of the scenario:

- **Scenario 1: intrinsic value allocation.** We use the ranking of intrinsic marginal valuations from Section 6.3.2 to determine the efficient allocation of 2.3 GHz and 3.4 GHz spectrum. [✂] REDACTED.
- **Scenario 2: Vodafone takes 2.3 GHz.** For this scenario, we assume Vodafone takes the entire 2.3 GHz band. [✂] REDACTED welfare losses of around £2.2bn in TP1. We then assume that competition in the 3.4 GHz band is based on intrinsic values alone, thus ensuring an efficient allocation from TP2 and minimising further welfare losses.
- **Scenario 3: EE and Vodafone take 3.4 GHz.** For this scenario, we assume that EE and Vodafone jointly acquire all the 3.4 GHz band. [✂] REDACTED H3G and O2 would still win 20 MHz each in 2.3 GHz. This minimises welfare losses in TP1, but 2.3 GHz alone is insufficient to address capacity issues in TP2, leading to a welfare loss in that period of around £2.3bn.
- **Scenario 4: EE and Vodafone win all PSSR spectrum.** In this scenario, EE and Vodafone acquire all spectrum in the 2.3 GHz and 3.4 GHz bands. This leads to total welfare losses in TP1 of £2.2bn and welfare losses of £3.1bn in TP2. Note that the combined welfare losses of £5.3bn far exceeds the sum of the welfare losses that consumers would suffer if EE and Vodafone only block O2 and H3G from accessing one of these bands.

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[73] We use a discount rate of 9%.

Table 4: Welfare losses owing to inefficient allocation of spectrum

	Allocation (in MHz) [✂] REDACTED			**Transition period 1**		**Transition period 2**	
		2.3 GHz	**3.4 GHz**	**Search costs**	**Quality welfare losses**	**Search costs**	**Quality welfare losses**
1	O2			£16m	£300m	-	-
	H3G						
	VF			Total: £316m		Total: -	
	EE						
2	O2			£121m	£2.1bn	-	-
	H3G						
	VF			**Total: £2.2bn**		Total: -	
	EE						
3	O2			£16m	£300m	£124m	£2.2bn
	H3G						
	VF			Total: £316m		**Total: £2.3bn**	
	EE						
4	O2			£121m	£2.1bn	£184m	£2.9bn
	H3G						
	VF			**Total: £2.2bn**		**Total: £3.1bn**	
	EE						

Source: NERA Economic Consulting

From this analysis, we draw the following conclusions:

- The efficient allocation of spectrum minimises welfare losses.
- Allocations in which O2 and H3G do not receive any 2.3 GHz or 3.4 GHz spectrum result in significant welfare losses for consumers in TP1 and TP2 respectively.
- An allocation in which O2 and H3G receive no spectrum in any bands would result in even larger welfare losses for consumers across the two transition periods.

6.4. Innovation benefits

In the Consultation, Ofcom raises the possibility that the PSSR spectrum could realise additional benefits though the early launch of innovative new services under the 5G banner (see, for example CD §5.80). We agree that 5G has the potential to bring substantial benefits for the UK and it is prudent for Ofcom to consider "5G readiness" when setting policy for mobile spectrum allocation. However, as we discussed in Section 0, many of the benefits associated with 5G will initially be realised through deployment of advanced 4G. At the point in time when 5G is ready to be deployed, most likely as part of a converged 4G-5G ecosystem, other spectrum options will be available. Accordingly, we do not believe that the 3.4 GHz band offers unique benefits that cannot be replicated with other spectrum.

Ofcom attach considerable weight to the possibility that an operator may need 100 MHz of contiguous spectrum to launch 5G services. This possibility is cited at CD §5.88 by Ofcom as a key reason for it selecting Option A over Option C in its remedies discussion. However, our deeper investigation in Section 0 reveals that the focus on large contiguous blocks is misleading. It appears that this is an engineer's description of an "ideal" deployment. The practical reality will be that nearly the same speeds can be realised by aggregating equivalent bandwidth across bands. Moreover, because 5G will almost certainly be designed as an evolution of 4G, rather than an outright replacement, decisions to deploy 4G in 3.4 GHz spectrum now is a more likely route to 5G subsequently being deployed than keeping the band clear for direct 5G deployment in due course.

Against this background, Ofcom's policy of treating the 3.4 GHz band as somehow distinct from other mobile bands is misguided. It should be treating it as another 4G capacity band, albeit with weaker propagation characteristics but some potential upside because of its link to 5G.

When 5G benefits do emerge, innovation benefits for consumers are likely to be maximised if every network has the capacity to launch such services. We are agnostic whether there is sufficient spectrum to support four completely separate 5G networks or whether some degree of spectrum sharing may ultimately be necessary. However, given Ofcom's commitment to maintaining four credible network providers, it would be inconsistent to allow award outcomes now that enable one or two parties to dominate mobile spectrum. The possibility that EE could monopolise the 3.4 GHz band, in addition to its majority holdings in the 1800 MHz and 2600 MHz bands, should be a source of alarm. Simply put, if this happens, there may not be enough spectrum available after 2020 for others to develop competitive 5G propositions.

In summary, allowing EE to bid for blocks of 100 MHz or more in the PSSR auction offers no prospect of welfare benefits through innovation before c.2022. It may, however, reduce future benefits from 5G, by reducing scope for competition in the provision of 5G services.

6.5. Dynamic competition benefits

As Ofcom notes at CD §1.15-1.16, it continues to attach great importance to "*real competition between four national network providers*." It further acknowledges that "*there is a risk that the current level of competition will reduce as consumer demand for mobile services increases. This is because there is an asymmetry in the amount of spectrum held by different operators. It means that some operators may be better placed to respond to increased demand than others*." In this section, we explore the impact of PSSR award outcomes that would leave O2 and/or H3G with constrained networks, while EE and Vodafone have significant capacity to absorb customers.

Our competition analysis is in three parts. First, we explore the relevant academic literature, which links capacity constraints to a softening of price competition. Second, we identify leading indicators of reduced competition in the UK mobile market, including evidence of market bifurcation and price increases. Third, we extend our valuation model to explore the potential magnitude of strategic value for Vodafone and EE from securing sufficient PSSR spectrum to block O2 and/or H3G [✂] REDACTED. We show that these values are large and, if crystallised in bids, could lead to very inefficient award outcomes.

6.5.1. Impact of capacity constraints on competition

Economic theory and evidence from other industries

There is a long standing tradition in industrial organisation studying the impact of capacity constraints on market competition. One of the earliest contributions in this area is by Kreps and Scheinkman (1983) who study a two-stage game in which firms first choose capacity and then compete on price.[74] They show that firms will choose Cournot quantities for their capacity and that price competition will set prices at the Cournot level rather than at marginal cost. The implication is that capacity constraints are an important factor determining competition in a market. Updates to this theory are summarised in Compte, Jenny and Rey (2003).[75] Studies that have explored this issue from an empirical perspective include Ilin and Shi (2016)[76] and Bresnahan and Suslow (1989).[77]

In competition economics, capacity constraints play a key role in the analysis of tacit price collusion. In repeated Bertrand price competition games, firms can maintain tacitly collusive prices if they believe that undercutting competitors could trigger a price war and thus harm future profits. When firms are subject to capacity constraints, their short term gains from undercutting competitors are limited which makes undercutting competitors less attractive.

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[74] David M. Kreps and Jose A. Scheinkman, 1983, Quantity precommitment and Bertrand competition yield Cournot outcomes, http://www.u.arizona.edu/~mwalker/501BReadings/Kreps&Scheinkman_3003636.pdf

[75] Olivier Compte, Frederic Jenny, Patrick Rey, 2003, Capacity Constraints, Mergers and Collusion, http://idei.fr/sites/default/files/medias/doc/by/rey/capacity_constraints.pdf

[76] Cornelia Ilin, Guanming Shi, 2016, Competition, Price Dispersion and Capacity Constraints: The Case of the U.S. Corn Seed Industry, http://ageconsearch.umn.edu/bitstream/236532/2/IlinShi2016.pdf

[77] Timothy F. Bresnahan and Valerie Y. Suslow, 1989, Oligopoly pricing with capacity constraints, https://annals.ensae.fr/wp-content/uploads/pdf/n1516/vol1516-13.pdf

Much of the empirical work focuses on the situation where the entire industry is capacity constrained. For example, Ilin and Shi (2016) show that once all firms are operating at their capacity constraint, none of them have an incentive to compete. The results are consistent with studies that highlight the potential for large welfare losses from delays in spectrum allocation on the mobile industry (although these have primarily focused on static efficiency losses rather than reduced competition benefits[78]). Most recently, NERA has undertaken a study for the GSMA which identifies a statistical link between high spectrum prices (which are often linked to constraints on spectrum availability) and higher prices and slower investment in 4G prices.[79]

The more relevant situation for our case, however, is one where only some players are capacity constrained. Here, the literature demonstrates that the presence of capacity constraints by itself reduces incentives for price competition, regardless of whether individual competitors are already producing at full capacity.[80] Logically, a tightening of these constraints would reduce the incentives for price competition even further. According to this line of argument – as developed by Compte (2003) – once at full capacity, a firm has no incentive to compete on price and also does not pose a credible threat to its competitors in terms of engaging in price competition. Meanwhile, having some firms with significant spare capacity (such as EE and Vodafone) is a deterrent to price competition by other firms. In particular, when one firm has sufficient capacity to serve its own customers as well as a significant share of those of a competitor, its spare capacity acts as a deterrent for its competitors to engage in a price war as they could lose significant market share and possibly their entire business.

Allowing large asymmetries in spectrum holdings to continue in the UK at a time when some networks are congested is therefore likely to reduce price competition:

- It reduces H3G's and O2's incentive to compete on price to attract new customers as they would not have spare capacity to serve them.
- Increasing Vodafone's and EE's spare capacity is a further deterrent for H3G and O2 to engage in price competition, as retaliation by Vodafone and EE could lead to significant losses in market share. Unless Vodafone and EE believed they could drive a competitor out of business, they have little incentive to engage in a price war, as the short-term gains (in terms of market share) would likely be more than offset by lower long-term revenues.

With respect to the mobile sector, predicting how these competition effects may play out is challenging owing to the lack of precedent for asymmetric capacity constraints. As we showed in Section 3, the current situation in the UK with two credible mobile operators

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[78] See, for example, Hazlett and Muñoz, 2004, A Welfare Analysis of Spectrum Allocation Polices. AEI-Brookings Joint Centre, pp. 4-18; and Hausman, J (1997), "Valuing the effect of regulation on new services in telecommunications", Brookings Papers on Economic Activity, Microeconomics.

[79] GSMA and NERA, Effective Spectrum Pricing: Supporting better quality and more affordable mobile services, forthcoming (February 2017).

[80] Olivier Compte, Frederic Jenny, Patrick Rey, 2003, Capacity Constraints, Mergers and Collusion.

having only 15% or less share of usable spectrum is exceptional. There is simply no precedent for observing how competition in pricing and provision of 4G data services will be impaired if two operators are chronically capacity constrained owing to lack of spectrum, while two others have surplus spectrum. Nevertheless, the lessons from the literature and other industries are that consumers will suffer owing to reduced competition.

The recent experience of Vodafone-Hutchison Australia (VHA) may provide an analogy. In mid-2009, Vodafone and 3 merged to create VHA in an effort to prepare for the impending smartphone revolution. However, while engineers at VHA were still primarily focused on the merger, its competitors, Optus and Telstra, had already been preparing for a surge in data usage for several years.[81] When the data market soared in 2009,[82] VHA's resources were stretched and base stations could not be built or upgraded quickly enough to cope with the demand. This led to a large number of network and customer service issues in 2010 and 2011.[83] VHA started investing heavily in its network from 2012 to enhance network stability, resiliency and coverage, but it continued losing customers until 2014 owing to enduring poor brand perception. VHA's market share fell from 24% in 2011 to 18% in 2014.[84] To this day, Telstra – which has a 53.3% market share – does not have to match VHA's mobile plans to attract and retain customers. While VHA charges $60 for an 11 GB monthly data plan, Telstra charges $70 for 10 GB.[85] This suggests that VHA is not "*able to exert an effective constraint on its rivals*" or, in other words, it is not a fully credible competitor (CD §4.6).

In summary, the literature, evidence from other industries and experience of VHA suggest a number of policy implications for Ofcom as it considers further spectrum allocation for mobile:

- Given current rates of growth in data demand, all operators in the UK will eventually hit their capacity constraints. To avoid general competition concerns resulting from capacity constraints, Ofcom must continue to release spectrum in a timely fashion.

- To preserve credible price competition between four-players, Ofcom must ensure that operators facing imminent capacity constraints [✂] REDACTED can access this spectrum on fair commercial terms. This may require blocking the possibility that they are outbid by rivals bidding based on strategic investment value.

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[81] News.com.au, 2015, How Vodafone came back from Vodafail, http://www.news.com.au/technology/gadgets/mobile-phones/how-vodafone-came-back-from-vodafail/news-story/65eb96d2487efc3b5d3ca251e4d259be

[82] In 2009 alone, the number of mobile subscription increased by 120%. See ACCC, 2010, Telecommunications competitive safeguards for 2008–2009, available at: https://www.accc.gov.au/system/files/ACCC%20Telecommunications%20reports%202008-09.pdf

[83] A consumer forum (www.vodafail.com) was launched in 2011 to raise awareness of the many problems and issues with VHA's network.

[84] ACCC, 2016, Competition in the Australian telecommunications sector: Price changes for telecommunications services in Australia, available at: https://www.accc.gov.au/system/files/ACCC%20Telecommunications%20reports%202014%E2%80%9315_Div%2011%20and%2012_web_FA.pdf

[85] We compare two 12-month post-paid plans. Prices were retrieved from VHA's website (http://www.vodafone.com.au/plans/state/sim/12-month/filter) and Telstra's website (https://www.telstra.com.au/mobile-phones/plans-and-rates#) on 5 September 2016.

- In situations when some operators are constrained, allocating spectrum instead to operators that already have a lot of spare capacity is likely to exacerbate competition concerns. The additional spare capacity acts as a deterrent for other firms to engage in price competition.

6.5.2. The situation today – evidence of capacity constraints starting to impact competition

In its assessment of current competition in the UK mobile market, Ofcom concludes at CD §4.1 that it "*is currently working well, with four credible MNOs and a range of MVNOs supporting strong retail competition. This is despite the fact that the existing spectrum holdings of the four MNOs are currently asymmetric*." With respect to high-level market share trends and the general level of prices, we agree. However, just because competition has been effective up to now is no guarantee that it will be effective in the future. A thesis of this paper is that spectrum-induced capacity constraints will dampen competition, but that consumer switching from constrained networks will likely lag these effects. Accordingly, given that capacity constraints are new and only started to be felt in traffic hotspots over the last two years, it is unsurprising that such effects have not yet shown up in market share data.

Ofcom argues at CD §4.147 that if O2 does not obtain any spectrum in the auction, it is "*unlikely that O2 would cease to be credible in the transition period. This does not rely on O2 necessarily retaining its current market position as it could still be a credible competitor with a smaller market share.*" Here, Ofcom appears to be failing to consider the difference between an operator that is losing market share because it is being out-competed in a fair market, and one that is unable to maintain a fully competitive proposition because it is capacity constrained. [✂] REDACTED.

In this section, we highlight evidence that capacity constraints and expectations that they will get worse are already shaping the behaviour of operators in ways that will ultimately harm consumers.

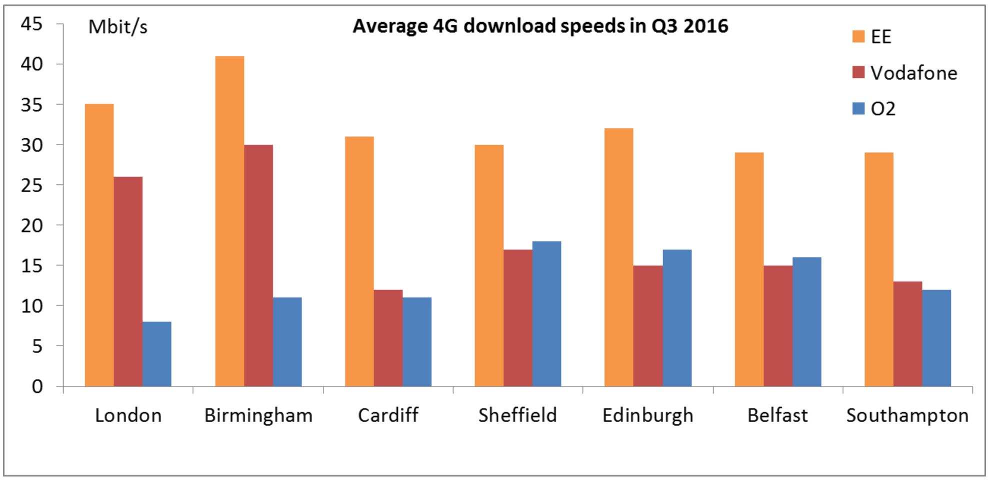
[✂] REDACTED.

Quality of service in London

As described in Section 6.3.1, there is now [✂] REDACTED. As illustrated in Figure 16, EE offers the best performance in all major cities, but Vodafone has the capability to match them, and has done so in London and Birmingham. [✂] REDACTED.

[✂] REDACTED.

Figure 16: Average 4G download speeds in 2013

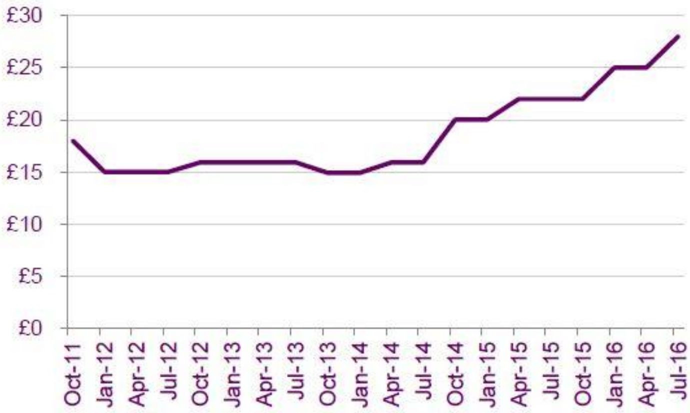


Source: Data from Ofcom's report, "Smartphone Cities", 16 December 2016

Softening of competition from H3G

As a late entrant, H3G has built its market share through attractive price plans for data use. At CD §A7.68, Ofcom praises H3G for leading certain innovations in the UK mobile market, for example its role in pioneering "All You Can Eat" data plans. However, over the past three years, H3G's competitiveness with respect to data plans has softened. As illustrated in Figure 17, the price for its unlimited data, 600 minute, SIM-only plan has almost doubled in this period.

Figure 17: H3G's unlimited data, 600 minute, SIM-only plan



Source: Reproduction of Figure A7.20 from CD §A7.41

It may be that H3G's former price levels were unsustainable in the context of a rapid growth in demand for data. Nevertheless, this rapid rise in prices should raise alarm bells that lack of capacity may be forcing H3G to use price to choke off demand. Indeed, we note that BT CEO Gavin Patterson is on record as suggesting that H3G should attempt to address its spectrum shortage by putting up its prices even more; this would obviously be in the interests of BT subsidiary EE, as it has the capacity to absorb H3G's customers, so is particularly well positioned to benefit from reduced price competition.[86]

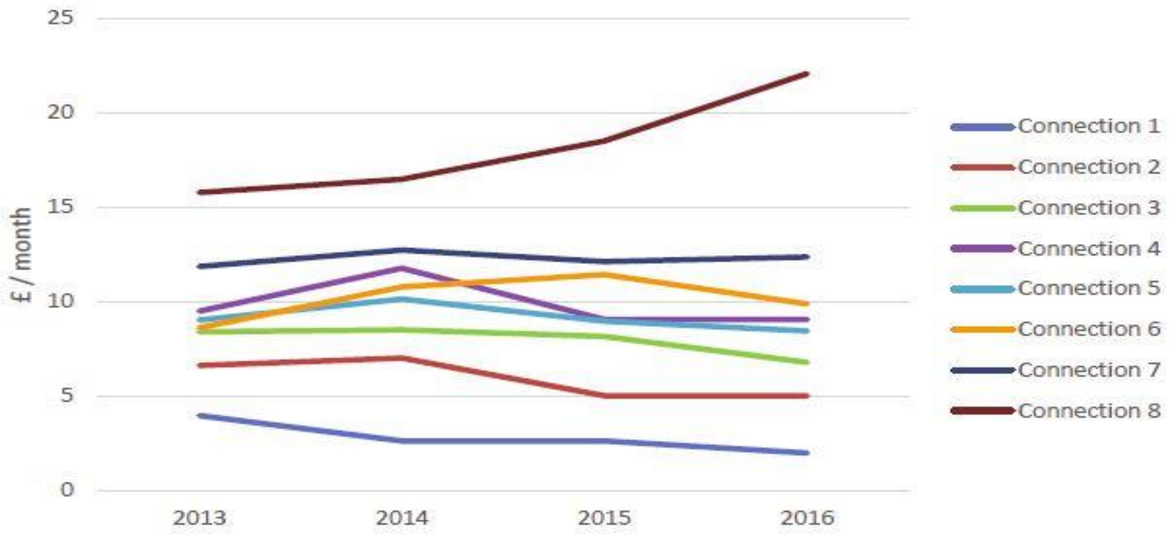
Evidence of market bifurcation

In previous mobile spectrum competition assessments and in the T-Mobile/Orange merger, Ofcom and the European Commission have expressed concerned about so-called "bifurcation risk", especially in the short-to-medium term. That is, that some parts of the retail market may only be serviceable by a subset of the four national wholesalers. In its first consultation on the PSSR award in 2014, Ofcom identified a risk that very asymmetric spectrum holdings could have a negative impact on competition, noting that a reduction in competition could take place because (for example) an operator with a low spectrum share might not be able to compete quite as strongly for some customer segments.[87]

[✂] REDACTED.

With market bifurcation first affecting the premium end of the market, we would expect to see evidence of rising prices in this segment. This is indeed the case, as illustrated in Figure 18, taken from Ofcom's competition assessment, the lowest available prices for most customer segments have remained largely unchanged (Connections 1 to 7). However, there has been an almost 40% increase in prices for premium connections (Connection 8 in the figure below) consisting of a premium handsets, 500 minutes, 200 texts and at least 5GB of data.

Figure 18: Lowest available prices for UK mobile services by customer segment



Source: Reproduction of Figure A7.16 at CD §A7.35

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[86] BT analyst briefing, October 2016, available at: http://seekingalpha.com/article/4016733-bt-groups-bt-ceo-gavin-patterson-q2-2017-results-earnings-call-transcript?page=19

[87] Ofcom, 2014, Public Sector Spectrum Release (PSSR): Award of the 2.3 and 3.4 GHz bands, paragraphs 7.47-7.48.

[✂] REDACTED.

6.5.3. Modelling the impact of strategic investment value

To support our analysis, we use our high-level valuation model to determine the additional "strategic investment" value that Vodafone and EE may gain from winning 2.3 GHz and 3.4 GHz spectrum, if this blocks O2 and/or H3G [✂] REDACTED. This is based on the "subscriber loss avoidance model" we used in the previous section to determine intrinsic value.

We make the following additional assumptions to generate strategic investment value:

- When other networks lose subscribers owing to network congestion, unconstrained networks will be able to attract these customers to their networks. We assume that these customers flow to other networks in a manner proportional to the amount of spare capacity on those networks.

- When other networks become constrained, price competition softens. Unconstrained networks will be able charge a premium over current prices. We use two regimes here:

    - 'Mild' assumptions about the softening of competition: three unconstrained networks receive a 2.5% boost of their cash flow margin, two unconstrained networks receive a boost of 5% of their cash flow margin; or one unconstrained network receives a 7.5% boost of its cash flow margin.

    - 'Aggressive' assumptions about the softening of competition: three unconstrained networks receive a 10% boost of their cash flow margins; two unconstrained networks receive a boost of 20% of their cash flow margins; or one unconstrained network receives a 30% boost of its cash flow margin.

- We assume a fairly symmetric allocation of 700 MHz and 3.6 GHz spectrum: Vodafone, EE and H3G are allocated 2x10 MHz each in 700 MHz (which translates into 10 MHz of downlink capacity); O2, EE and H3G are allocated 30 MHz each in 3.6 GHz, and Vodafone is allocated 20 MHz at 3.6 GHz. This reduces the strategic value for EE and Vodafone, as O2 and H3G have some long-term relief to their constraints.

- We determine the net present value (NPV) of cash flows for all possible allocations in 2.3 GHz and 3.4 GHz. The total value for a particular number of 10 MHz lots is then the minimum NPV of cash flows if that operator is allocated that particular number of lots less the NPV of cash flows if the operator does not win any spectrum in the auction. Strategic value is the difference between total value and intrinsic value.

Error! Reference source not found. plots Vodafone's intrinsic and strategic value for 2.3 GHz spectrum. As noted previously, its intrinsic value is small and consists of future value of using this spectrum when it would otherwise hit its capacity limit after 2020. In contrast, its strategic value for this spectrum is very high.

Comparing this to the intrinsic valuations of H3G and O2 for this spectrum, we note the following:

[✂] REDACTED.

[✂] REDACTED and [✂] REDACTED plot strategic value for 3.4 GHz spectrum for both Vodafone and EE. [✂] REDACTED. There is no efficiency gain from allowing either operator to bid for more than [✂] REDACTED in 3.4 GHz. The risks are, however, substantial as both EE and Vodafone have huge values for blocking O2 and H3G from securing spectrum beyond that. [✂] REDACTED. The results indicate that either operator has a potential incentive to act unilaterally or multilaterally to block O2 and H3G.

[✂] REDACTED.

EE and Vodafone could also try to collectively block H3G and O2 from winning any spectrum. [✂] REDACTED.

These outcomes depend on a mix of unilateral action and/or tacitly coordinated action by EE and Vodafone to block rivals from winning spectrum. As Ofcom notes at CD §4.187, the costs of unilateral action at 2.3 GHz fall entirely on Vodafone (assuming EE is excluded from bidding there) but the benefits are split between them. Our analysis demonstrates that Vodafone can secure enough strategic value to potentially outbid O2 and H3G, and justify unilateral action (in this scenario, it should be indifferent to the likelihood of EE also reaping benefits). Ofcom should also be alive to the possibility that Vodafone thinks that O2 and H3G undervalue spectrum or are budget constrained, and therefore places a higher probability of unilateral action being successful than would otherwise be the case. Ofcom should not therefore discount the possibility of a very inefficient outcome at 2.3 GHz owing to Vodafone exploiting strategic investment value.

With respect to 3.4 GHz, Ofcom's current proposals would also allow one bidder to acquire the entire band, and unilaterally block O2 and H3G. A more plausible scenario, however, is that EE and Vodafone tacitly coordinate to together block their rivals. As Ofcom explains at CD §4.197, such coordination is difficult to achieve with certainty, given information rules that hide the identity of bidders. Nevertheless, given the size of strategic value at stake for both bidders, which exceeds the intrinsic value for O2 and H3G, it certainly cannot be ruled out. For example, [✂] REDACTED.

In conclusion, the possibility of grossly inefficient outcomes owing to operators bidding on the basis of strategic investment value cannot be ruled out, while the costs of precluding them are very low. This implies that there is a strong public policy case to impose competition measures that eliminate the possibility of such outcomes.

7. Remedies for the PSSR award

When designing a spectrum award, Ofcom has a series of ex-ante measures at its disposal that it can adopt as “remedies” to influence the potential outcome of a spectrum award. The most powerful measures are spectrum caps and set asides, as these constrain the range of possible auction outcomes. Other measures, such as the choice of auction format, level of reserve prices or information policy, may play an important role in influencing the behaviour of bidders and thus make “undesirable” auction outcomes less likely, but do not preclude them.

In this section, we set out our views on the competition and other measures proposed by Ofcom. In Section 7.1, we discuss the role of auction design in encouraging or discouraging bidder behaviour that could lead to undesirable outcomes. We strongly support Ofcom’s choice of format and detailed rules, including its proposals to further constrain withdrawal rules. However, these measures cannot by themselves address the risks to efficiency and competition identified in this report. In Section 8.2, we consider Ofcom’s assessment of options for competition measures. We agree that it has broadly identified the appropriate range of options, given scope for modification. However, we think that Option A (Ofcom’s initial preference) is not strong enough to prevent the possibility of a very inefficient and anti-competitive award outcome. In Section 8.3, we make our own suggestions for competition measures that Ofcom could adopt, which build on Ofcom’s Options B and C.

7.1. The role of auction design

When determining the auction format for this award, Ofcom identified its main choice as being between the simultaneous multiple round ascending auction (SMRA) and the CCA, the format it used for the UK 4G auction. We strongly support Ofcom’s choice of a variant of the SMRA, and welcome the fact that Ofcom has not opened up this choice to further consultation.

The PSSR award has three particular features which would leave it vulnerable to bad outcomes if a CCA format were used[88]:

1. **Declining marginal values for spectrum**. There is a large amount of spectrum available in this award, and Ofcom proposes that all (or most) bidders be allowed to bid for large quantities of spectrum. Bidders can also be expected to have strictly declining marginal values for incremental spectrum, based on its role in alleviating capacity constraints (we view any premium for large contiguous blocks for 5G as small compared to capacity values). In this situation, using a CCA may introduce perverse incentives for bidders to express exaggerated incremental values for very large packages of spectrum over smaller ones as a way of threatening to impose opportunity cost on rivals. This would distort price discovery, and create a risk of excessive prices and inefficient outcomes if bidders misplay this strategic game. [✂] REDACTED.

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[88] There is a growing body of literature describing strategic bidding in the case of the CCA (and how this differs from SMRAs), from both a theoretical and case study perspective. See, for example: Marsden, R & Sorensen, S, “Strategic Bidding in Combinatorial Clock Auctions”, a chapter in Bichler, M and Goeree, J, Handbook of Spectrum Auction Design (forthcoming, Cambridge University Press).

2. **Exceptionally high asymmetries between major bidders**. The presence of large and predictable asymmetries in intrinsic value, between O2 and H3G on the one hand and EE and Vodafone on the other, deepens the risk of strategic play in a CCA. [✂] REDACTED.

3. **High strategic value**. We have shown that the strategic investment value to EE and Vodafone from blocking O2 and H3G from addressing their capacity constraints through TP1 and TP2 is large. The CCA pricing rules, which discourage demand reduction, strengthen the incentives for bidders to include strategic investment value in their bids. This greatly increases the risk of inefficient bids and outcomes if a CCA is used.

The SMRA is a much better choice for addressing these concerns. Under this format, if a bidder attempts to price drive in a band where it wants spectrum, it is also driving its own price. This makes such tactics less desirable. In addition, when compared to a CCA, price discovery in an SMRA makes outcomes more predictable. This better addresses Ofcom's concern at CD §2.23 that the auction should be designed to secure "*that bidders should not feel they would have bid differently when they see the final result*".

We also welcome other aspects of Ofcom's detailed rules which make strategic bidding behaviour more difficult:

- **Generic lots.** Ofcom proposes a two stage auction, with lots initially sold on a generic basis in an approach that borrows features of a clock auction. This simplifies the bidding process, eliminates opportunities for strategic play such as signalling across specific lots, and allows bidders greater security that they will be awarded contiguous spectrum.

- **Information policy.** Ofcom has proposed a relatively constrained information policy, including only releasing limited information to bidders about the level of excess demand during the auction. This is a prudent safeguard in this auction [✂] REDACTED.

- **Withdrawal rules.** Ofcom has placed restrictions limiting the scope for withdrawals of standing high bids and imposing tough penalties on bidders whose withdrawals cause lots to go unsold. These measures provide additional protection against price driving behaviour, as bidders cannot exploit the withdrawal rules to escape the consequence of inadvertently finding themselves as standing high bidder on more spectrum than they really want. Ofcom's proposed amendments to the withdrawal rules, as described at CD §6.1-6.48, place further limits on the scope for withdrawals, and as such reinforce the deterrent to strategic bidding. We agree with Ofcom that only bidders with partial standing high bids should be allowed to withdraw demand, as the circumstances under which a bidder might have a rationale based on intrinsic value to withdraw any other bid from a band are remote.

Notwithstanding these points, Ofcom's SMRA rules do not eliminate incentives for price driving nor strategic value-based bidding. They simply create an environment less friendly to such behaviour. Given the exceptional scale of strategic investment value associated with blocking a rival from addressing spectrum-induced capacity constraints, such behaviour will remain a concern under any format. Ultimately, Ofcom must either decide that it can live with such risks or adopt spectrum caps to constrain their impact.

Ofcom has also expressed concern about the opposite problem: under certain conditions, bidders participating in its SMRA format may have incentives to engage in demand reduction. From a welfare perspective, this is not necessarily a problem, as successful demand reduction tactics may simply result in an efficient outcome at lower prices. Nevertheless, demand reduction raises two concerns from a policy perspective. First, in auctions (like this one) where multiple lots are available, some bidders may win too little spectrum because they reduce demand too much. Second, the auction may be perceived as realising “too little” revenue relative to true market value.

In relation to the PSSR auction, we think that Ofcom’s analysis exaggerates the risks of demand reduction in the case of tight spectrum caps while ignoring such risks in the case of lax spectrum caps. We suspect that Ofcom makes this error because, in the absence of having any model of the value of PSSR spectrum to individual bidders, it may have a limited grasp of the likely competitive dynamics for the auction ahead.

Ofcom cites the risk of demand reduction as an objection to remedy Option B, which would de facto exclude both EE and Vodafone from bidding for 2.3 GHz spectrum. In this case, it is concerned that O2 and H3G might tacitly collude to share the spectrum. Obviously this is possible but should Ofcom really be concerned about this risk? Our valuation model suggests not, [✂] REDACTED. If Ofcom has other concerns, such as the price being too low, then it could alternatively raise the reserve price for 2.3 GHz or adopt a threshold price approach, as described at CD §5.115.

In contrast, Ofcom fails to consider the risk of inefficient demand reduction under its proposed Option A, where Vodafone is unrestricted in both bands and EE is unrestricted at 3.4 GHz. [✂] REDACTED.

7.2. Competition measures

In Section 5 of the Consultation, Ofcom identifies five potential options for competition measures, as summarised in Table 5. All of these involve spectrum caps or reservations that to a greater or lesser extent impose constraints on the ability of EE and Vodafone to bid for PSSR spectrum.

Table 5: Summary of Ofcom’s options for competition measures

	Description
Option A	Cap of 255 MHz (about 42%) applied only to immediately useable spectrum Prevents EE from acquiring 2.3 GHz (but would permit it to acquire 3.4 GHz)
Option B	Cap of 150 MHz (about 25%) on immediately useable spectrum Prevents both EE and Vodafone from acquiring 2.3 GHz (but would allow both to acquire 3.4 GHz)
Option C	Cap of 255 MHz applied to immediately useable spectrum (as in option A) combined with an overall spectrum cap set at 340 MHz (around 37% of the sum of currently held

	spectrum, PSSR spectrum and 700 MHz spectrum) Prevents EE from acquiring 2.3 GHz and limits it to 85 MHz of 3.4 GHz and imposes minor constraint on Vodafone
Option D	Reserving two lots, each of 20 MHz of 2.3 GHz spectrum, for operators with smaller spectrum holdings (e.g. less than 90 MHz) or new entrants Prevents EE and Vodafone from acquiring 2.3 GHz spectrum
Option E	Cap of 255 MHz (about 30% of mobile spectrum) Prevents EE from acquiring any spectrum in this award and imposes substantial constraint on Vodafone

Source: Ofcom at CD §5.18

Ofcom poses two questions with respect to these measures:

- *Question 3: Do you agree we have identified the right options to address our competition concerns?*

  We broadly agree that these provide a suitable range of options for consideration, particularly because Ofcom makes clear that it will consider variants to those options. One important caveat is that Ofcom should amend its definition of usable spectrum to incorporate a Transition Period 2 (from 2019-20, when 3.4 GHz and 1400 MHz become available) in addition to Transition Period 1 (from 2017-18, when only 2.3 GHz is added to the stock of usable spectrum). If TP2 is considered, then it is follows logically from Ofcom's own reasoning that competition measures are required for 3.4 GHz as well as for 2.3 GHz.

- *Question 4: Do you agree with our assessment of the options we have identified for promoting competition in the auction?*

  We disagree with Ofcom's assessment of the relative merits of the options. Ofcom's choice of Option A, although offering some benefits by excluding the possibility that EE might bid strategically for 2.3 GHz, is insufficient to address the competition concerns that Ofcom has identified. Ofcom has identified capacity as the critical factor that links 2.3 GHz spectrum to competition, and has identified its primary concern as being the preservation of four credible operators. However, Option A leaves open the possibility that one bidder (Vodafone) could block its capacity constrained rivals (O2 and H3G) from winning any 2.3 GHz spectrum. Furthermore, Ofcom's justification for selecting Option A over Option C is based on the potential benefits from EE using a huge swathe of 3.4 GHz to launch early 5G services. We have shown that such benefits are illusionary – the more plausible path to 5G is a converged 4G-5G ecosystem with 5G launch after 2020. EE does not need 3.4 GHz spectrum for this, as it already has 2.6 GHz spectrum and could supplement this later with 3.6 GHz and 700 MHz, if necessary.

  Throughout its analysis, Ofcom weighs the risk of being too "interventionist". This bias against intervention may serve it well in many other policy situations but it is inappropriate here. Our efficiency and competition assessment demonstrates that downside risks from being too interventionist are much smaller than the downside

> risks associated with an inefficient outcome in which O2 and H3G are blocked from winning the spectrum they need [✂] REDACTED. This is because the starting point for the auction in spectrum asymmetry is so extreme.
>
> Notwithstanding this point, we recognise that a degree of pragmatism may be required with respect to competition measures. A large share of the benefits to consumers from O2 and H3G securing 2.3 GHz come from them deploying this spectrum as early as possible in 2017. Thus, it is overwhelmingly in the interests of consumers that the award of 2.3 GHz happens as soon as possible. On this basis, there is a certain logic in Ofcom avoiding measures, such as a spectrum reservation (option D) or very tight overall caps (option E), that are likely to be particularly contentious and harder to justify without Ofcom engaging in a much deeper and time consuming assessment of efficiency and competition. Accordingly, the solution we put forward – which combines modifications to Options B and C – is presented as a compromise. It eliminates the very worst case outcomes but still gives much more flexibility to EE and Vodafone than our assessment suggests is necessary.

Below, we provide specific comments on each of Ofcom’s five options.

Option A: Cap that blocks EE from bidding for 2.3 GHz

Under Option A, Ofcom proposes a cap of 255 MHz, which would preclude EE from bidding for any 2.3 GHz spectrum, but would not constrain any other bidder. Ofcom claims that this approach would address its main concern relating to a very asymmetric distribution of immediately useable spectrum. We disagree. The real problem is not one operator (EE) having too much spectrum but two operators (O2 and H3G) having too little. As Ofcom’s approach would allow Vodafone to buy the entire 2.3 GHz band, it leaves open the possibility of an outcome that is grossly inefficient and harmful to downstream competition.

If Ofcom wants to ensure a pro-competitive outcome, it must take some action to constrain Vodafone in the 2.3 GHz band. This is because, as we demonstrated in Section 6.5.3, Vodafone has potentially huge strategic investment value from blocking O2 and H3G in acquiring 2.3 GHz spectrum. Although the benefits of blocking would be shared with EE, we showed that the unilateral benefits to Vodafone may provide sufficient incentive for strategic bidding. If Vodafone engaged and succeeded in such behaviour, the welfare losses for consumers are substantial. [✂] REDACTED.

We also see no logic in setting a cap on usable spectrum for TP1 at 255 MHz. This would be a dangerous precedent for future awards that implies it is acceptable to have an operator in a four-player market to have 42% of usable spectrum. [✂] REDACTED.

A further problem with option A is that it does nothing to address competition concerns in TP2. For the reasons we set out in Section 6, Ofcom can only foreclose clearly bad outcomes for UK consumers if it adopts individual competition measures for both the 2.3 GHz and the 3.4 GHz bands.

Option B: Cap that blocks EE and Vodafone from bidding for 2.3 GHz

Under Option B, Ofcom proposes a cap of 150 MHz (about 25%) on immediately useable spectrum. This would have the effect of blocking both EE and Vodafone from acquiring 2.3

GHz, but would place no restrictions on either party to bid for 3.4 GHz. From an efficiency perspective, we see merit in this approach, as it would eliminate the possibility of either EE or Vodafone blocking O2 and H3G from winning 2.3 GHz spectrum. The residual range of outcomes are all ones that have good efficiency properties, thus mitigating concerns about welfare losses. Furthermore, this approach is less prescriptive than Option D, as it allows the market to determine how 2.3 GHz is split between O2 and H3G (or a third party).

Ofcom also proposes a variant of this option at CD §5.52, which is a cap at 180 MHz (about 30%, which would have the effect of allowing Vodafone to bid for up to 20 MHz at 2.3 GHz. This variant is less interventionist and also largely achieves the competition goal of removing Vodafone's ability to exploit its strategic value to block its rivals. If Vodafone is limited to buying no more than 20 MHz, it could not stop one of O2 or H3G from taking the remainder or the two operators from splitting 20 MHz equally. In this case, it has no certain path to realise strategic investment value, so is more likely to bid based on intrinsic valuation. This approach also addresses Ofcom's concerns that Option B could enable O2 and H3G to share the spectrum at a low price, possibly below Vodafone's own intrinsic value (although this issue could also be addressed by other measures, such as a higher reserve price or a threshold price).

An equivalent option to a 180 MHz cap would be a 37% cap on usable spectrum in TP1 AND a precautionary cap of 20 MHz per bidder. A 180 MHz cap has the advantage that it retains flexibility for one of O2 or H3G to bid for more than 20 MHz, while constraining Vodafone. The equivalent approach eliminates this flexibility, but has the advantage that it treats all bidders symmetrically.

As with Option A, such caps do nothing to address competition concerns in TP2. The measures we describe here are therefore not sufficient by themselves to address efficiency and competition concerns. Additional action would be required in relation to 3.4 GHz band.

Option C: Two caps, one on immediately usable spectrum and one future usable spectrum

Under Option C, Ofcom proposes two caps:

1. 255 MHz on immediately usable spectrum, which would preclude EE from bidding for 2.3 GHz (as in option A); and

2. 340 MHz on usable spectrum in the future (around 37% of the sum of currently held spectrum, PSSR spectrum and 700 MHz spectrum), which would limit EE to buying no more than 85 MHz of 3.4 GHz and imposes minor constraints on Vodafone.

We strongly support the general principle here that there should be two caps, one to address competition concerns in TP1 and another to address concerns in TP2. This is the only approach that can address the risk of large welfare losses in either time period owing to inefficient outcomes. Furthermore, given the evidence that 3.4 GHz will be a crucial band for adding 4G capacity and that large blocks are unlikely to be a critical path to 5G, this is the option that Ofcom should adopt based on its own reasoning at CD §5.94.

The specific caps proposed by Ofcom would, however, be inadequate to eliminate the competition and efficiency concerns we have identified. We discussed our concerns with

Option A above; we suggest that Ofcom instead adopts one of the two variants of Option B that exclude EE from 2.3 GHz but allow Vodafone to bid for up to 20 MHz.

In relation to the second cap, our main concern is the arbitrary inclusion of 700 MHz, which will not be available for several years after 3.4 GHz. Consistent with Ofcom's logic that caps should be on usable spectrum, Ofcom should instead define this cap to only include spectrum that is usable in TP2. In this case, a circa 37% cap would translate to 310 MHz, which would limit EE to acquiring no more than 55 MHz and Vodafone to no more than 130 MHz in the 3.4 GHz band. This approach would impose a more meaningful constraint on EE and further weaken the scope for tacit collusion between EE and Vodafone to block rivals from the 3.4 GHz band (as all the costs but only half the benefits accrue to Vodafone).

We recognise that a c.36-37% cap on usable spectrum in each transition period has the advantage of precedent. This would be consistent with the approach taken for the UK 4G auction and the approach that Ofcom initially proposed for the PSSR auction in Ofcom's first consultation on the PSSR award[89]. Ofcom should further consider whether a 37% cap in TP2 is tight enough. This still leaves open the possibility that EE and Vodafone could acquire all or most of the 3.4 GHz auction, which our model tells us is not plausibly an efficient outcome. If Ofcom instead adopted a 35% cap (295 MHz), this would limit EE to 40 MHz and Vodafone to 110 MHz, thus further reducing the likelihood that these two operators bid to monopolise the band. A 35% cap would also be more in line with international norms on spectrum concentration in four-player markets, as discussed in Section 4.1.3.

Option D: 2.3 GHz set asides

Under this option, Ofcom would reserve two 20 MHz lots for two bidders other than EE and Vodafone – almost certainly O2 and H3G. Such a reservation would correspond directly to our expected outcome based on intrinsic business case modelling in Section 6.3.2. From an efficiency perspective, we see merit in this approach, as it may well be the most efficient outcome for 2.3 GHz and, if not, any other outcomes that may be more efficient are probably not much more so, so the risk of a welfare downside is small. Moreover, the remedy is very effective in eliminating any possibility of EE or Vodafone blocking these operators from expanding capacity.

There are, however, other problems with this approach. Firstly, the approach leaves little room for the market to determine allocation, so would be a significant step away from standard Ofcom policy. Also, unless reserve prices are increased, it may raise concerns that O2 and H3G are being de facto awarded spectrum on the cheap. Finally, Ofcom itself has not identified the evidence necessary to support this approach. Even if Ofcom relies on evidence from consultation responses, such as this one, it would need to go through the process of replicating the associated models, which may mean further consultation. If this has the effect of delaying the auction, the process may destroy the very welfare benefits that it is trying to protect.

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[89] In previous consultations on the PSSR award, Ofcom have proposed caps of 36% (October 2013) and 37% (November 2014) on holdings of spectrum in relevant bands. See: Ofcom, 2.3 and 3.4 GHz spectrum award, 16 October 2013; and Ofcom, Public Sector Spectrum Release (PSSR), 7 November 2014.

Option E: 30% cap per operator

Under this option, Ofcom would impose a tight cap on total spectrum holdings, well below its previous precedent of c.36-37%. This approach would have the effect of preventing EE from buying any PSSR spectrum and significantly constraining Vodafone. From an efficiency perspective, we see little downside from this approach. Neither EE nor Vodafone have any significant need for additional capacity spectrum in the next four years, so such a measure should have little or no downside for welfare. Also the cap is not as tight as it sounds, as (a) EE would still have 32% of all mobile frequencies even if it acquires no PSSR spectrum; and (b) Ofcom plans to award more spectrum after 2020 that could meet EE's long-term needs, including launching 5G.

We do, however, recognise some concerns with this approach. Firstly, given the uncertainty over the timetable for 3.6 GHz and 700 MHz, a cap that prevents EE from acquiring any spectrum may be considered overly harsh. In sensitivity analysis on our model, it is possible to make a case that EE may need 20 MHz of 3.4 GHz to avoid capacity constraints from emerging around 2020, assuming it maintains its high market share. Secondly, by itself, the measure does not prevent Vodafone taking the whole 2.3 GHz band, so it is not an effective remedy for efficiency and competition concerns in TP1. Finally, as with Option D, Ofcom has not identified the evidence to justify such a tight cap and the process of doing so may take too long.

7.3. Recommendations

Spectrum caps

Based on our review of Ofcom's options, we recommend the following competition measures:

1. **A 35% cap on usable spectrum,** to apply in both:
   (c) Transition Period 1: Current spectrum plus 2.3 GHz
   (d) Transition Period 2: Above spectrum plus 1400 MHz and 3.4 GHz
2. **Two precautionary band-specific caps:**
   (c) 20 MHz per operator at 2.3 GHz
   (d) 100 MHz per operator at 3.4 GHz

The purpose of measure (1) is to prevent any party securing too much spectrum in either TP1 or TP2, and thus increase the likelihood of outcomes in which all operators can secure adequate capacity. Consistent with Ofcom's Option A, measure (1a) would prevent EE from bidding for 2.3 GHz, while measure (1b) would prevent EE from bidding for very large packages in the 3.4 GHz band. On efficiency and competition grounds, we think there is a very strong case for setting these caps at 35% or even lower. We recognise, however, that this is less than the c.36-37% cap level that Ofcom has hitherto adopted.

The purpose of measure (2) is to foreclose particularly undesirable outcomes for specific bands that are still possible under a global cap. Measure (2a) would prevent any bidder from winning more than 20 MHz at 2.3 GHz, thus precluding the worst case where Vodafone leverages strategic investment value to buy the entire band. If Ofcom is concerned that this unduly constrains O2 and H3G, it might alternatively adopt a 180 MHz cap for TP1. Measure (2b) would prevent any operator winning a block larger than the maximum identified as useful for delivering 5G. This is proposed as a safeguard against future spectrum asymmetry in the (admittedly unlikely) case that broad contiguous spectrum holdings in the 3.4-3.8 GHz band become critical for realisation of the full 5G benefits.

Other measures

We identify here a number of soft measures that Ofcom could also adopt to promote an efficient auction process:

3. Ofcom could commit now to undertaking an **in-depth review of spectrum holdings, competition and efficiency effects** before the next auction. Specifically, it would be helpful if Ofcom makes it clear that it will adopt an open mind with respect to the level of universal caps for the next auction of 700 MHz and 3.6GHz. By leaving open the possibility of a future usable spectrum cap as low as 30%, Ofcom would send a powerful message to EE and Vodafone that bidding aggressively in this auction (based on strategic value) might lead to them being shut out of 700 MHz.

4. Ofcom could provide an **update on plans for clearing 700 MHz and 3.6 GHz**, and the timetable for their award. If bidders are reassured about the timing of availability of future spectrum, they can more accurately value any time premium for PSSR spectrum. If bidders then bid based on intrinsic value, it is more likely that bidders who have an immediate need to deploy PSSR spectrum will be successful.

5. Ofcom could give warning to bidders for 3.4 GHz that they may be required to engage in **industry discussions regarding reconfiguration of the broader 3.4-3.8 GHz band**, so as to avoid long-term fragmentation of the band. Such a process may involve bidders that are not making full use of their spectrum for 4G being required to relocate within the wider band. This approach could help address any long terms concerns Ofcom may have about the possible requirement of bidders for larger blocks for 5G, if this turns out to be relevant from 2022.

These further measures would make it easier for operators to identify relative valuations for PSSR spectrum and other bands available later, and thus promote straightforward bidding based on intrinsic value.

Annex I: Detailed modelling of small cells

This annex presents a detailed model of small cell deployments in LTE networks, as introduced in Section 5.4. The purpose of the model is to show why capacity gains are less than might be expected based on traditional models for densification of macrocells, and provide insights into optimal small cell numbers.

Frequency allocation for small cells

Each small cell will need to be assigned radio frequencies. Typically, when an MNO reaches the point that small cell deployments are being considered, they have already deployed all their available frequencies within the macrocell layer. They have the following options for assigning small cell frequencies:

1. Macrocell and small cells share the same carrier. (Termed “shared carrier”.)
2. Macrocells and small cells each have a dedicated carrier created by splitting the original carrier in two. (Termed “dedicated carrier”.)
3. Resource blocks (RBs) are set aside for users on the edge of small cells using enhanced inter-cell interference cancellation (eICIC)[90] where the macrocell does not transmit on these RBs. (Termed “RB”.)

With a shared carrier both macrocell and small cell transmit at the same time on the same frequencies. For users close to one base station (eg the macrocell) but far from another (eg the small cell) this can work as the wanted signal level will be high and the interfering level low. But for a user on the edge of the small cell interference can occur as they will experience a relatively weak signal from the small cell and a relatively strong one from the macrocell. The inclination of the network is then to hand them over to the macrocell, effectively reducing the coverage radius of the small cell and hence the percentage of users it can serve.

With a dedicated carrier, part of the frequency allocation is removed from the macrocell to be made available on the small cells. This resolves all interference issues between macrocells and small cells, but reduces the capacity of the macrocell and hence the combined macrocell/small cell combination for low numbers of small cells.

The eICIC approach sits somewhere in between these. It effectively dedicates sub-parts of a frequency band, as needed, to particular users who are towards the edge of the small cell. As a result, it might be thought it would deliver the highest performance. However, as the sections below discuss this is not always the case.

Simulation environment

The simulation area is based on a sector of a cell. For simplicity the sector is assumed to be 90° and square (rather than 120° and pie-shaped). This makes placement of the small cells much simpler. This simplification does not materially change the results. Hence the macrocell is at the origin (0,0) of the square simulation area.

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[90] For an explanation of eICIC see http://www.3gpp.org/technologies/keywords-acronyms/1576-hetnet

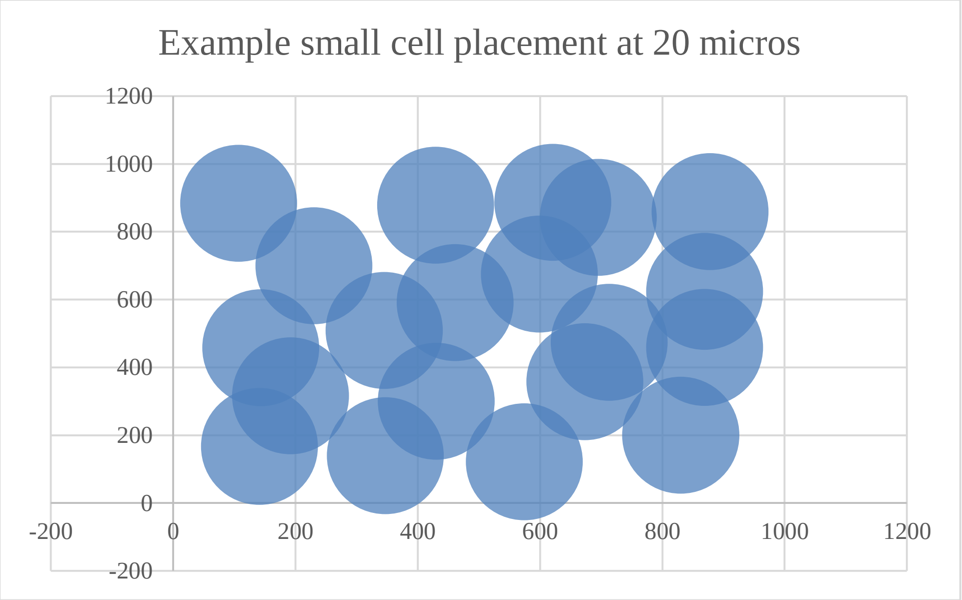
Small cells are then placed throughout the area. There are two approaches used here:

1. Random with minimal overlap. The location of the small cell is selected randomly such that the cell lies entirely within the macrocell area. The small cell is then tested for overlap with any other small cells already sited. If there is overlap a new random location is selected. If, after 100 attempts to find an overlap-free location, none can be found, then 10% overlap with other small cells is allowed and the process repeated. The allowed overlap percentage then increases to 20% and so on. The results of a typical deployment using this approach with 20 small cells in the macrocell area is shown in Figure 1. This approach is intended to mimic real-life where MNOs will seek to avoid overlap between small cells as far as possible but will be limited by the sites available for them to mount their base stations. It is worth noting that even with 20 small cells there are still many gaps in coverage and something like 30 or more would be needed to ensure complete contiguous coverage.

2. Hot spots. Here a number (*n*) of hotspots are assumed within the simulation area. The first *n* small cells are placed to cover these hotspots (with the ability to be offset by a chosen amount to reflect the reality of siting constraints). Any remaining small cells are placed randomly as above. Optionally, overlap with small cells covering hotspots can be given a higher penalty value such that overlap is less likely.

Next users are placed randomly across the simulation area. Where there are hotspots, then the selected percentage of users are placed within the coverage area of these hotspots. Users are also assigned to be indoors or outdoors using a percentage selected in the simulation. Indoor users are then assigned randomly to a floor within the building of between level 0 and 5. However, within hotspots all users are assigned to level 0 on the assumption that the small cell would have been sited to be able to capture all the traffic in the hotspots (e.g. in a stadium or shopping mall). A typical distribution in a dense deployment scenario is illustrated in Figure 19.

Figure 19: A typical distribution of small cells in a dense deployment scenario



Source: NERA Economic Consulting

Note that only outdoor small cells are considered. Indoor small cells can be effective but MNOs typically find it difficult to gain access to the buildings to install them, and uneconomic in that one small cell per floor of each building might be needed. Instead, users tend to self-provide coverage with Wi-Fi which meets their data needs although there may be some issues with voice calls.

User data rates

For each user their maximum downlink data rate is calculated. This is determined according to the signal-to-interference ratio (SINR) using a best-fit curve to the performance of a typical LTE system – essentially a look-up function that takes the SINR and returns the data rate in bits/s/Hz.

The process of determining the SINR is as follows, with most steps being further explained below.

- Determine whether the user is using the macrocell or a small cell. This becomes the “serving cell” and all others are “interfering cells”.
- Calculate the signal level from the serving cell.
- Calculate the interference level from all interfering cells – potentially including the macrocell and other small cells.
- Calculate the noise floor according to standard equations.
- The SINR is signal level minus interference and noise.

The determination as to whether the user is camped onto a macrocell or small cell depends on the deployment strategy as follows:

- Shared. The model selects the cells with the strongest signal level.

- Dedicated. As above, the model selects the cells with the strongest signal level.
- RB. The model determines the difference between the small cell and macrocell and if this difference exceeds a user-set threshold, it selects the small cell. This allows small cells to optionally be preferred even when their signal level is lower than the macrocell, effectively extending their range.

The signal level is calculated as follows:

- Macrocell. Two models are used. For distances above 1km (rarely encountered in practice as the model is generally user-set to have a maximum macrocell range of 1km) the Hata urban propagation model is used. For distances below 1km, the Walfisch line of sight (LoS) urban model is used[91].
- Small cell. A classic two-path microcell model with breakpoint at 100m is adopted. In addition, a further step-function increase in path loss is added at the assumed maximum range of the small cell.
- Indoor. A user-set percentage of subscribers are located indoors and a building penetration is added to the path loss. For macrocells, the penetration loss is constant at 15dB. For small cells the loss is assumed to be low near the cell where the angle of visibility into the building is high, rising to higher penetration levels as the distance increases and the angle of visibility down the street becomes increasingly oblique. The model assumes 10dB penetration up to 20m distance, rising at 0.2dB for each metre further from the transmitter (so at 70m the penetration loss would be 20dB). Penetration loss to users above floor 1 from small cells is assumed to be infinite as the small cell antenna is typically located below this level.
- Transmit power levels are assumed for macrocells and for small cells.

By the end of this process each user has an assigned data rate that they are able to receive at.

Network capacity

The users are assigned a desired data volume. In this simulation, this is set at a relatively high level equivalent to 5Gbytes/user/month and 2,000 subscribers in the 1km^2 sector to ensure the network is fully congested (which allows maximum network capacity to be determined). The time each user needs to receive their data is equal to the data volume divided by their determined data rate. This time is effectively their percentage of the cell capacity used (so if they need 60s to receive their typical hourly data requirements they use 1/60th of the capacity of their serving cell). This process continues until all the capacity of a cell is used at which point the data carried by that cell is totalled. The cell capacity is determined by the size of the carrier and any allocation set aside for resource blocks. The simulated capacity is then the sum of all the capacity across the small cells and the macrocell combined.

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[91] For a description of both propagation models see Haslett C, “Essentials of radio wave propagation”, Cambridge University Press, 2008.

The associated network cost can be simply computed as the capital expenditure (capex) and operational expenditure (opex) for the macrocell, and the capex and opex for each of the small cells deployed. This allows metrics such as cost/busy hour Mbyte carried to be calculated.

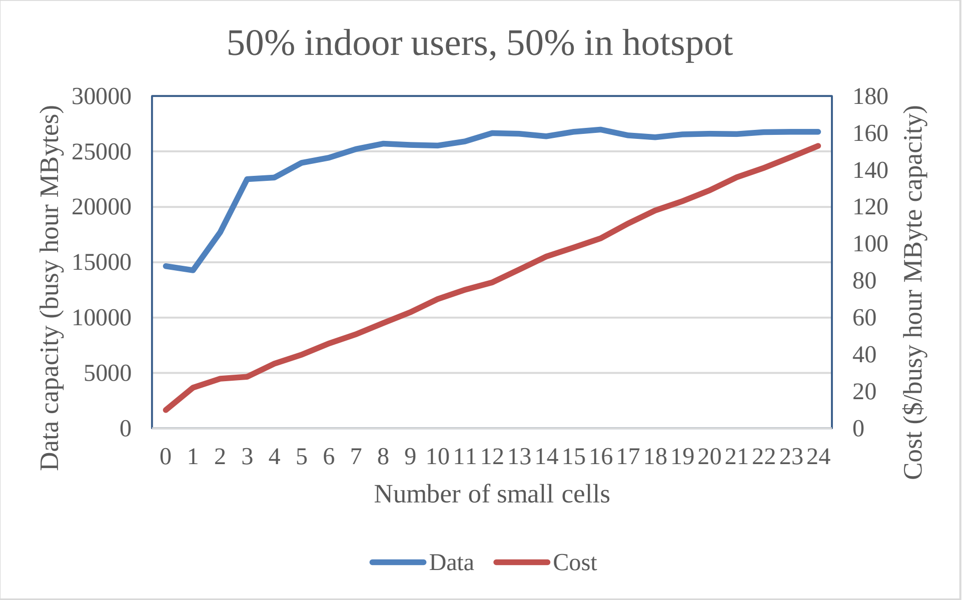
Calculating results

In generating results it is necessary to set percentages for the number of users indoors and the percentage of users located in hotspots within the macrocell. These percentages will vary from one macrocell to another and over time. For that reason a range of different scenarios are modelled below.

The model considers all possible spectrum assignment approaches described above and selects the optimal policy. As might be expected, for small numbers of microcells (typically less than two) a shared carrier is optimal. After that the model prefers a dedicated carrier until extremely large numbers of small cells (typically around 20) are reached when a RB approach with most RBs (70%) being used in the small cell is optimal. Further assessment of the results shows that the differences between the dedicated and RB approach is relatively small, suggesting that it is not critical which of these is chosen. The somewhat counter-intuitive nature of the results also indicates the complexity of the situation and the reason why detailed modelling is needed to understand the outcome.

The results for the scenario with three hotspots carrying 50% of traffic, 50% indoor users are plotted in Figure 20:

Figure 20: Results for 50% indoor users and 50% spread across three hotspots



Source: NERA Economic Consulting

The results show:

- The first small cell actually reduces the capacity. This is because it reduces the macrocell capacity through generating interference by more than the capacity it adds.
- The second and third small cells which are targeted at hot spots, add substantial capacity as they can reuse the same frequencies used by the first small cell and so do not materially increase interference. These hotspots have been selected to be well-spaced around the macrocell and so do not have significant interference between themselves[92]. With three small cells the sector capacity has been increased by 50%.
- Going from four to around nine small cells provides some small gains. Gains are limited because the small cells cannot serve many of the indoor users and so do not attract large volumes of traffic. At this point the overall capacity increase is around 75%.
- Beyond this, capacity is essentially static as additional small cells increasingly overlap with existing small cells.
- Costs per unit of data carried rise throughout, being three times higher for three small cells, six times higher for nine small cells and over ten-fold beyond this. Hence, small cells are an expensive way of providing further capacity.

From these results we might conclude:

- Deployment of small cells in traffic hotspots can be effective.
- There is little point in deploying beyond the number of hotspots in a sector, and more generally beyond about three-four small cells per sector.
- With a complete layer, capacity gains of around 75% on the case where there are no small cells are possible, but higher gains (e.g. 10x) cannot be achieved.
- Small cells significantly increase the cost per Mbyte of traffic carried, which would reduce profitability or require ARPU increase.

If there are no hotspots, the results are as shown in Figure 21.

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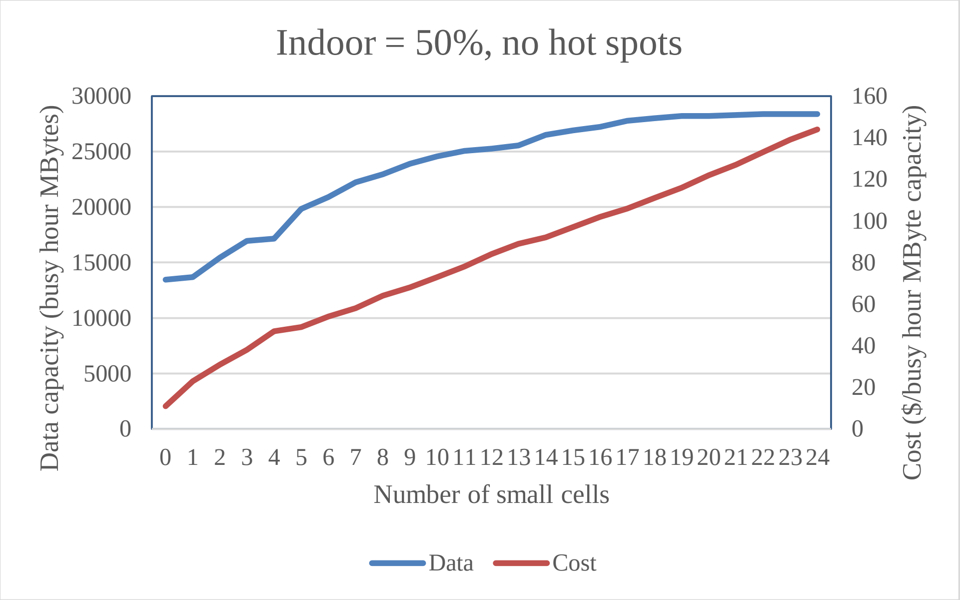
[92] If the hotspots were close together the results would be worse owing to the interference between them.

Figure 21: Results for 50% indoor users and no hotspots

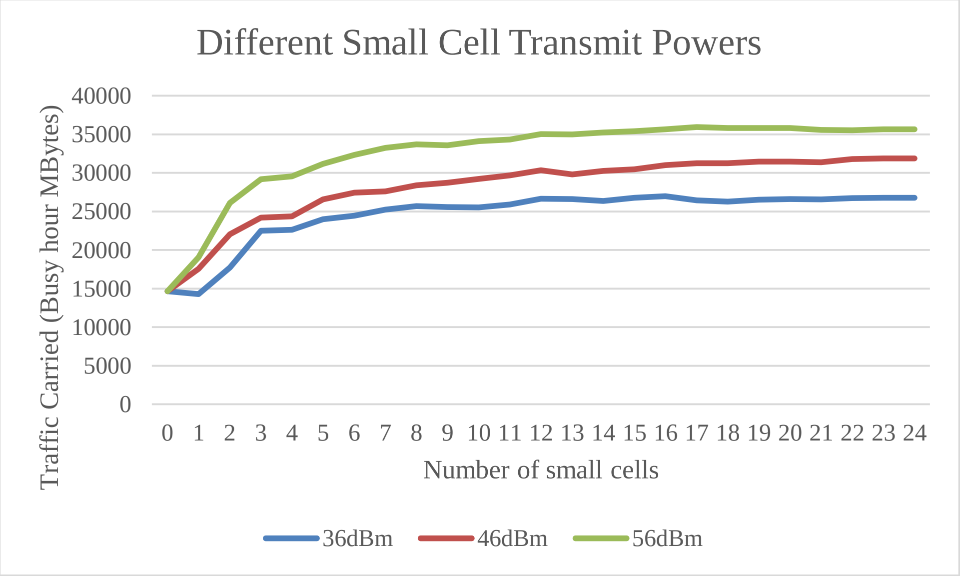


Source: NERA Economic Consulting

This shows a steadier climb in capacity to around 10 small cells, with a gradual plateauing out after that at a similar level of capacity increase as the previous scenarios. Costs rise somewhat steadily throughout and are higher at lower numbers of small cells as might be expected from the fact that the first few cells do not carry the same traffic volumes as when there are hotspots.

There are many different variables that can be explored. Figure 22 shows how the traffic levels change as the small cell transmit power is increased.

Figure 22: Different small cell transmit powers

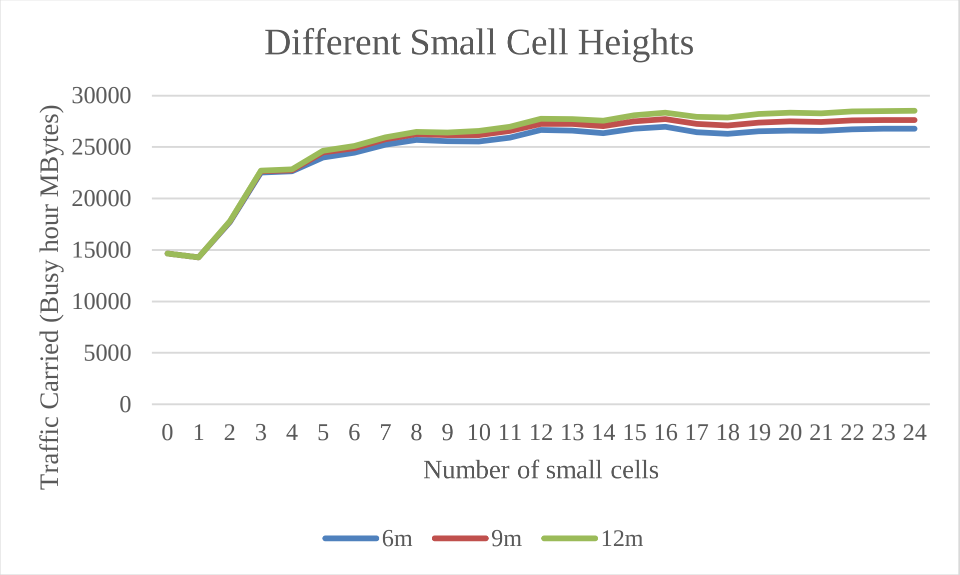


Source: NERA Economic Consulting

Note that it is generally not possible to source small cell base stations with transmit powers materially above 36dBm. For example, Nokia supply small cell base stations with a maximum transmit power of 10W (40dBm). Even if it were possible, the figure shows that only small improvements in overall capacity are possible. At 10 small cells the gains at 36, 46 and 56dBm are 74%, 99% and 130%, respectively. While higher power levels do improve indoor penetration, they also lead to higher interference levels both between small cells and to the macrocell limiting their capacity gains.

Alternatively, the small cells can be placed differently in the street. Placing to one side of the street compared to the centre makes little difference unless the street is extremely wide. A side placement improves building penetration on one side but degrades it on the other, albeit not by much in either case. Different heights could also be considered. Figure 23 shows the impact of changing the small cell mounting height.

Figure 23: Different small cell heights



Source: NERA Economic Consulting

Note that there may not be any flexibility in height placement – for example if lampposts are used it may be that the base station has to be deployed on top of the lamppost. Higher deployments improve building penetration on upper floors but also increase interference between small cells and to the macrocell. As the figure shows, the two effects cancel such that there is minimal difference in capacity with small cell height.

There is clearly a very large difference between the 1000% capacity improvement that might have been expected with 10 or more cells and the 75% or so that is seen in practice in the most likely scenarios. This is because:

- Frequencies have to be taken from the macrocell, reducing its capacity, but it is only the macrocell that can serve users in many of the buildings and in the gaps between small cells. If the macrocell becomes heavily congested it limits further gains in cell capacity.

- Small cells increasingly interfere with each other as they get closer together, reducing the effective capacity of each.
- Small cells, especially outside of hotspot areas, may not be able to attract many subscribers and hence may be under-utilised even while the macrocell is congested.

Conclusions

The key conclusions are:

1. Small cells are not a source of infinite capacity expansion. The best possible improvement is around 100% increase (2x) over a sectored 1km radius macrocell.
2. The optimal number and deployment strategy vary depending predominantly on the presence of hotspots in the sector and also the percentage of indoor subscribers. In most cases deploying more than around three small cells is not worthwhile.
3. A hot-spot strategy will nearly double the cost of carrying traffic in the sector on a $/bit basis compared to using a macrocell alone. A dense layer will result in a six-fold cost increase and a complete layer more than a ten-fold increase.
4. Capacity improvements beyond these levels will require indoor picocells. These have not been modelled but typically improve capacity owing to the shielding offered by the building which reduces interference.
5. The situation is complex, requiring a cell-by-cell evaluation of optimal strategy.

The implications for MNOs are significant. It will not be possible to use outdoor small cells as a way to substantially add capacity in the manner previously thought. This could leave an MNO that has already deployed all of its spectrum and all other capacity enhancement approaches in a position where it is no longer able to grow capacity to meet increasing demand absent being able to access additional spectrum.

Annex II: Valuation model for PSSR spectrum

This annex describes the model we use to determine network capacity and valuations for UK operators in Section 6. The model shows the networks that will become congested under various spectrum availability scenarios.

Overview of model

The network capacity model is an Excel spreadsheet based calculation which determines:

- the level of capacity that is likely to be demanded by subscribers based on assumptions of data demand growth;
- the level of capacity that an MNO can provide based on improving spectrum efficiency and spectrum holdings; and
- subscriber losses and movements owing to network congestion.

We then use the model to determine the intrinsic and strategic values for each of the four UK operators associated with specific PSSR spectrum allocation scenarios in the following way:

- Intrinsic value is estimated based on the loss of cash flows from those subscribers that cannot be served with the available capacity and leave the network.
- Strategic value takes this a stage further and assumes that these lost subscribers are captured by the operators with excess capacity. The model further assumes that when networks are constrained in the UK market, operators with excess capacity are able to charge higher prices. Hence, an operator may try to acquire spectrum above its intrinsic value to cause a competitor to shed subscribers which it can capture and also to soften price competition.

[✄] REDACTED.

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