# 2. Understanding the radio spectrum, auctions, and the UK case

Tackling public policy problems always involves mastering a certain amount of subject-specific background. To explain what is happening in spectrum auctions I need to say a few words about the radio spectrum in the first section, and about how auctions can be run in the second section. To help keep things concrete, the last section of the chapter outlines the UK's experience with spectrum auctions.

## 2.1 Radio spectrum: the basics

### Summary

- The radio spectrum is the range of electromagnetic radiation frequencies where information can be transmitted using radio waves. The focus in this book is on the frequencies used for mobile services, chiefly denoted in terms of mega-Hertz (MHz) or giga-Hertz (GHz).
- Frequency bands differ in their technical characteristics, with a trade-off between range and bandwidth. Equipment development also makes some bands more desirable, given that mobile handset markets are global. While a band can be used over time for different technologies, certain bands are prioritised for carrying each new generation of technology, as most recently with 5G.
- There is regulation at country level to manage interference between spectrum users. In addition, radio transmissions cross national boundaries, so international coordination is managed through regulation at different levels: at global level, in world regions (like Europe), and bilaterally between neighbouring countries.
- New bands for mobile spectrum come from a range of sources. They may have been used previously by public sector or commercial users, or made available by technology advances (as occurred when TV broadcasting moved from analogue to digital technology, creating a 'digital dividend' of bands freed up for mobile use).

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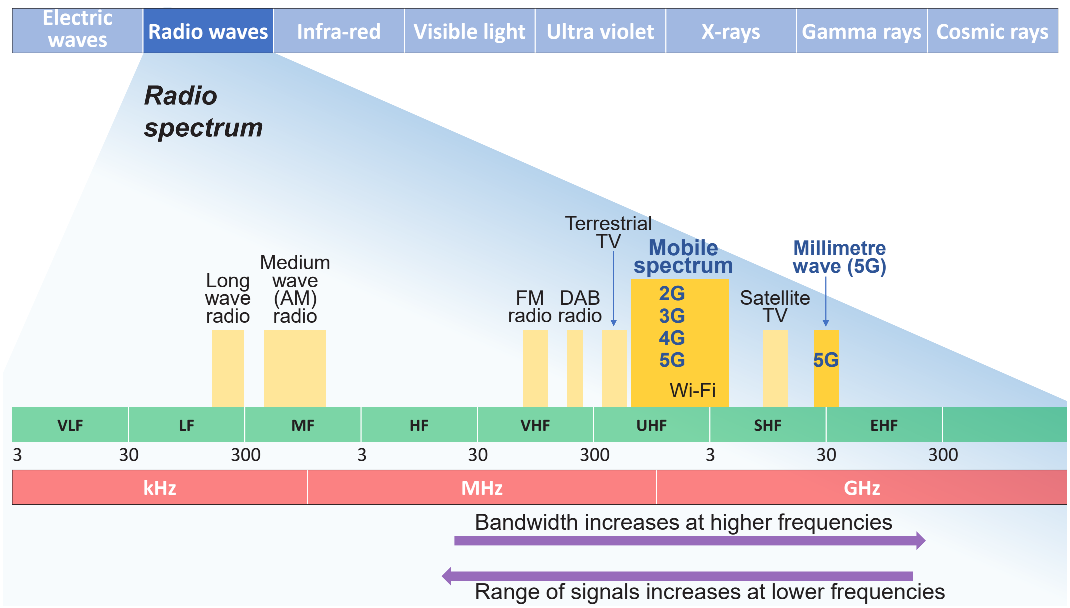
The 'radio spectrum' denotes the range of frequencies over which it is possible to transmit information by means of radio waves. Radio waves are a form of electromagnetic radiation, and the top bar of Figure 2.1 shows that they fall between electric waves on the one hand, and infrared radiation on the other. The figure also shows how radio waves can in turn be split up according to their frequency, denoted in Hertz, or multiples of thousands as kilo-Hertz ('kHz'), millions as mega-Hz ('MHz'), or thousand-millions as giga-Hz ('GHz').[1] Different parts of these frequencies within the radio spectrum are used for radio broadcasting, television broadcasting, and mobile services, as well as many other uses.

Radio spectrum is a natural resource owned by society. It is an adaptable input that can be used for a huge array of public and private wireless services. Each national government affects the use of spectrum in its territory, by deciding the allocation of rights to make radio transmissions. Because radio signals in neighbouring frequencies or locations can interfere with each other, each country issues licences for rights to make radio transmissions, to manage interference between spectrum users. In the case of cellular or mobile telecommunications services, the allocation decisions also determine which firms become the country's mobile operators, normally through exclusive licences for specified frequencies including terms and conditions set by the regulator. Within these limits, operators have flexibility to use their allocated spectrum to provide connections over their radio network between a base station and consumers' devices such as smartphones, to transmit calls, texts, and mobile access to the internet. Each mobile network provides wide area coverage so that its customers can receive services where they live, work, and move around. In addition, the amount of network capacity provided in each area affects the quality of services, such as the speed of internet access, as well as the number

**Figure 2.1. An overview of the radio spectrum used for radio, television, and mobile services**




Source: Author.[2]

Notes: VLF Very low frequency, LF Low frequency, MF Medium frequency, HF High frequency, VHF Very high frequency, UHF Ultra high frequency, SHF Super high frequency, EHF Extremely high frequency.

of customers that can be served. Each network therefore needs to invest in building base stations to provide both coverage and capacity using the spectrum it holds. For example, the population or country area covered by an operator is affected by commercial considerations, but also by the coverage requirements normally included in licence conditions set by the regulator. The amount of capacity can vary substantially between areas, with much more needed to serve high demand in densely populated parts of the country than in low-density rural areas.

The bottom arrows in Figure 2.1 indicate a technical trade-off between the range of the radio signals and the amount of information that can be transmitted, which is termed bandwidth. For instance, we can compare medium wave (AM) and frequency modulation (FM) radio. Broadcasts of medium-wave radio stations use lower frequencies and so provide wider geographic coverage. But because they have less bandwidth, their quality of sound for speech or music is lower than that offered by FM radio stations, which broadcast at higher frequencies with smaller coverage footprints. For mobile networks, this trade-off means that greater information can be carried at higher frequencies, such as faster data speeds, but more base stations need to be installed to cover a country's territory. Therefore, higher frequencies are especially suitable for providing additional network capacity ('capacity spectrum'), whereas lower frequencies allow wide area coverage to be provided at lower cost ('coverage spectrum').

## Mobile spectrum bands

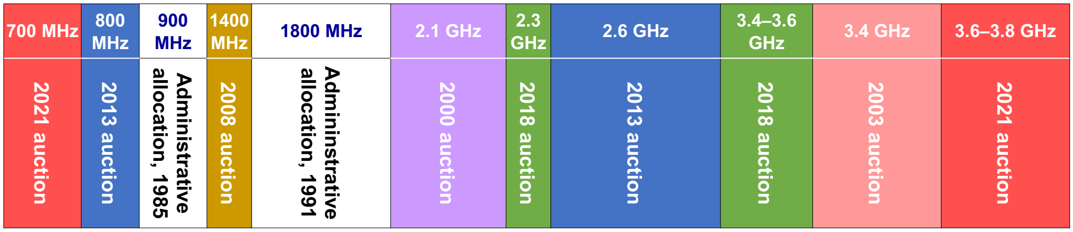
Different frequency ranges are organised into spectrum bands, and the main ones for UK mobile services are shown in Figure 2.2. The first few bands on the left-hand side are lower-frequency coverage spectrum, and the bands on the right-hand side are higher-frequency capacity spectrum. The bands all fall within the set of frequencies shown in Figure 2.1 that offer an especially attractive balance between range and bandwidth. In addition, new technology developments bring ever higher frequencies into use for mobile networks – for instance, for 5G services the millimetre wave spectrum from around 20 GHz upwards which is well beyond the right-hand side of Figure 2.2.

The times when different bands were allocated in the UK and the methods used are also shown in Figure 2.2. The earliest bands (coloured white) were allocated administratively in 1985 and 1991. Auctions were first used in 2000 to allocate the band shown coloured purple, and then in 2003 (pink). There was a decade gap before the bands in blue were auctioned in 2013, with the bands in green following in 2018, and in red in 2021.

As a scarce resource, most radio spectrum is in use, but changes in technology and international and national regulation can lead to the repurposing of bands. The bands in Figure 2.2 became available from a range of sources. Historically, the public sector and broadcasting have been major users of spectrum now used for mobile. The low-frequency bands included in the 2013 and 2021 auctions are sometimes referred to as the 'digital dividend', because they were made available by moving terrestrial television broadcasters to alternative frequencies as part of the shift from analogue to digital broadcasting technology. The bands included in the 2018 auction were previously used by the Ministry of Defence.

In nearly all countries, mobile services are delivered to the public through competition between mobile operators. Competitive markets usually deliver desirable outcomes for consumers and the economy, even if there can be exceptions. Competition applies pressure on firms to reduce their costs, economise on resources, and attract customers by offering lower prices and new or better services,

**Figure 2.2. Mobile spectrum bands and how they were allocated in the UK**




Source: Author from Ofcom auction documents.
Notes: Both frequency and amount of spectrum are denoted in MHz or GHz. The label is the frequency band and the relative amount of spectrum in each band is indicated by the width of the column.

such as through innovation reflecting the latest technological developments. Competition can empower consumers through greater choice, allowing them to 'vote with their feet' if they are dissatisfied. Competition also generally enhances the level of productivity in the economy.[3]

Some mobile operators are owned in whole or in part by governments, and others are private companies. Economies of scale in mobile networks lead to oligopolistic markets, usually with three to five competing mobile network operators in each country (with additional local operators in some countries). In the retail market, there are also further retail competitors, such as Mobile Virtual Network Operators (MVNOs) who do not have their own radio networks but rely on obtaining wholesale services from network operators. Examples in the UK are well-known consumer brands such as Tesco Mobile, or landline operators like Sky and TalkTalk. In the UK in 2022 there are four national mobile network operators – EE, H3G (whose brand name is 'Three'), Telefónica (using the brand name '$O_2$'), and Vodafone. These private corporations hold rights to use all the spectrum bands in Figure 2.2, acquired either via administrative allocation in 1985 and 1991, or via competing in spectrum auctions since 2000 (or through post-auction licence trades). For operators, holding a licence is a critical 'upstream' input and resource. The pattern of spectrum holdings between operators affects the intensity of their 'downstream' competition at the wholesale level to supply MVNOs and in the retail market, where consumers buy their mobile subscriptions and bundles of data services, texts, and telephone calls.

For each network operator the composition of bands in its spectrum portfolio matters, as well as the amount of spectrum held, because bands differ in their technical characteristics. We have seen that lower-frequency spectrum is more valuable in providing coverage in rural areas, such as sub-1 GHz bands at 700 MHz, 800 MHz, and 900 MHz. This is because the greater transmission range means that fewer base stations are needed, thereby economising on network costs. However, in areas with a large volume of traffic there is a limit to how much this matters, because a base station using a single frequency band will not provide enough capacity for services to all the network's customers in that area. One important way to augment capacity is to serve the geographic area with two or more base stations (sometimes called network 'densification'). In this case the theoretical maximum range of the frequency band is not the binding constraint, and having higher-frequency capacity spectrum offers bandwidth advantages. Other ways to augment network capacity include deploying more spectrum and using the latest technologies that achieve more data-carrying capacity per MHz.

The development of mobile equipment is also very important for the valuation and use of spectrum. Handsets are part of a worldwide market, and different bands are prioritised for each wave of mobile technology. For example, the first bands allocated in the UK to mobile operators were 900 MHz in 1985 and 1800 MHz in 1991, both initially used for 1G technology. Over time, use of these bands was progressively converted (or 're-farmed') to the later technologies of 2G, 3G, 4G, and in due course to 5G. The first band deployed in 3G handsets was 2.1 GHz, awarded in the 2000 auction. Early 4G spectrum included the 800 MHz and 2.6 GHz bands in the 2013 auction, but there was also equipment development for the pre-existing 1800 MHz band, so that in the UK this was the first band used for 4G technology. For 5G, the early bands in Europe have been at higher frequencies (due to their bandwidth advantages), especially the last three blocks on the right-hand side of Figure 2.2, which together span the frequency ranges of 3.4–3.8 GHz. In time, new equipment developments should enable any of the bands in Figure 2.2 to be re-farmed for 5G technology.

Across countries there is often similarity in the frequency bands used for mobile services, reflecting equipment manufacturers' economies of scale in producing handsets, so that it is difficult for all but the very largest countries to go their own way in choice of spectrum bands for mass-market services like cellular mobile. But there are variations between regions and continents, due to differences in historical spectrum use and priorities. For instance, while 900 MHz and 1800 MHz were the earliest bands used for mobile services in the UK, in the Americas the initial bands were 850 MHz and 1900 MHz.[4] Since radio transmissions cross national boundaries, a complex web of coordinating regulation is also needed at different levels. Some is global, some in large world regions (like Europe), and others bilateral between countries that share borders. The worldwide regulatory body is the International Telecommunications Union (ITU), which holds a World Radiocommunication Conference (WRC) every three to four years.

Whether regulators decide to use auctions or another method to allocate mobile bands, they will necessarily have to make a range of choices about the regulatory conditions for licences, including:

- Geographic scope: In the UK, mobile spectrum licences have usually been defined on a national basis, but in some other countries there are regional or local licences (such as Australia, Canada, India, and the USA).
- Services or technology: Historically, licences restricted spectrum use to specific services or technologies to manage interference. However, over time there has been a move to greater flexibility through terms that are more technology-neutral.
- Duration: Because the investment needed to create a mobile network requires firms to incur large sunk costs, mobile spectrum licences tend to last for many years, for example 10, 15, or 20 years. At the end of this period, there are renewals or a competitive selection process. In some countries like the UK, companies have been assigned licences of indefinite duration, with no specified end-date.

## 2.2 Introduction to auctions

When licences are initially allocated, the regulator can use different methods to decide who gets to hold a spectrum licence. Because mobile services are a technologically and commercially dynamic field, it is especially difficult for a regulator to judge which will be the most efficient licensees for periods stretching many years into the future. One simple approach is 'first-come, first-served', where licences are allocated in the order of firms applying for them. However, where there is excess demand from companies for spectrum bands, this is not an effective way to secure economic efficiency, maximise

## Summary

- Licences for mobile spectrum bands can be allocated to companies using administrative methods (such as a ‘beauty contest’ or a lottery) or via spectrum auctions.
- An auction is one type of market mechanism to sell items, where the outcome is determined based on eliciting information through bids from competing buyers about their willingness to pay.
- There are many possible auction formats. One is an open, ascending-price auction as used in fine art auctions. Other auction formats are more suitable for radio spectrum, given differences in objectives and context, most commonly the Simultaneous Multiple Round Ascending Auction (SMRA) or the Combinatorial Clock Auction (CCA).
- Prominent objectives of spectrum auctions are efficient allocation and public value, not just revenue (even if that tends to dominate media coverage).
- Unlike the single item in a fine art auction, spectrum auctions usually award multiple blocks of spectrum simultaneously to several winning bidders who may regard them as substitutes or complements to varying degrees.
- There is usually only a handful of companies bidding in spectrum auctions, given that mobile markets are oligopolies (due to economies of scale and scope), increasing the opportunities for strategic bidding.
- With these challenges, there is no perfect spectrum auction design, and experts embedded in practical public policy processes contribute to good judgement of the inevitable trade-offs.


benefits to consumers, or yield revenue for the government. In the past, lotteries were used in the USA at times, with luck alone determining which companies were initially successful (followed by the potential for subsequent licence trading). More usually there is a competitive allocation process. Before the 1990s such processes often took the form of a ‘beauty contest’, where the regulator applied specified criteria to judge the allocation between bidders. In the UK only the two original bands (900 MHz and 1800 MHz) in Figure 2.2 were administratively allocated through a beauty contest, but that method continues to be used to allocate spectrum for broadcasting.

Auctions with monetary bids are the other main competitive process. An auction is a type of market mechanism used by an auctioneer to sell (or buy) items, where the outcome is determined based on eliciting information through bids from competing buyers (or sellers) about their willingness to pay (or sell). For example, in an auction for a famous painting, dynamic interaction between competing buyers determines both the winner as the highest bidder and the price it pays. Compared to other allocation methods, auctions have the advantage of using a very transparent criterion to select who gets what. Money is an objective metric unlike the opaque, subjective judgement calls that can be features of beauty contests. Using monetary bids is suitable where the interests of consumers and public value are reflected in the regulatory conditions of sale, such as licence obligations to provide widespread mobile coverage and safeguards to promote downstream retail competition.[5] In the UK,

Figure 2.2 shows that, once adopted, auctions have been used to allocate the large majority of mobile spectrum (80 per cent).

Auctions have been used throughout world history for selling a wide variety of goods and services. A few examples are auctions for commodities, flowers, fish, companies, residential houses, antiques, broadcasting rights, service contracts for sport stars (such as cricketers in the Indian Premier League[6]), government Treasury bills, electricity, oil exploration and development leases, emission permits, and subsidies (an example from 2021 being environmental protection of turtle doves[7]). Auctions involve a structured bidding process amongst rivals to determine the winner and set the price. Of course, in contrast, many other products and services are bought and sold at prices posted by the seller, such as buying food from a supermarket or a mobile phone subscription from a retail communications provider. Even if there is sometimes room for haggling over the price, this tends to be a bilateral process between one buyer and one seller.

In the popular imagination, an auction often conjures up an image of an auctioneer at a podium with gavel in hand selling an item, such as a fine art painting, to multiple potential buyers in the room. The auctioneer responds to a previous bid by seeking bids at the next price up, and rivals in the room announce ever higher prices, until there is a single winner. This was the process used to sell the most expensive painting sold at auction, Leonardo da Vinci's *Salvator Mundi*, for $450 million in 2017.[8] However, this is just one specific context for an auction using one of many possible formats, and auctions can be structured in many different ways.[9]

The context for spectrum auctions is the different players involved and their interests:

- Auctions are organised and run by a regulator, whose chosen design depends on its objectives, such as allocating the spectrum in economically efficient ways, and promoting downstream mobile competition and extensive mobile coverage. To achieve these objectives, and with measures in the auction to safeguard competition and extend coverage, the regulator wants to incentivise bidders to make straightforward bids of the values they place on the spectrum in the auction. Assigning spectrum to the operators with the highest values is likely to deliver the largest benefits to the public. It is also important that the process is fair and seen to be fair, especially given the large sums of money involved. In many countries, the regulator is an independent agency, such as Ofcom in the UK or Anatel in Brazil, with its own statutory duties and authority to make decisions within a defined remit, separate from government and the political process. However, in some countries that regulatory role is performed by a state ministry, such as 'Innovation, Science, and Economic Development Canada' or the Department of Telecommunications in India.
- The government sets the overall direction of policy, and sometimes more detailed policy goals. In addition to boosting efficiency, competition, and coverage, ministers and top administrators are interested in the significant revenue that can be raised by spectrum auctions. Without an independent regulator, the governmental and regulatory functions for the auction can be performed by the same public organisation (as in Canada and India).
- The bidders in spectrum auctions normally include existing (incumbent) operators – in the UK: EE, H3G, Telefónica, and Vodafone – and sometimes also potential new entrants. Operators acquire spectrum licences at lump-sum prices set dynamically in the auction, and they take on the risk of using the spectrum to provide and sell services to earn profits, which can turn out to be higher or lower than they expected at the time of the auction. These firms are motivated by complex profit and commercial goals, and given the relatively small number

of bidders in spectrum auctions, they can often further their business goals by bidding strategically instead of straightforwardly. For example, self-interest might lead a bidder to seek to improve its outcome, winning spectrum at lower prices through bid strategies to exploit reduced intensity of competition in the auction. Or it might attempt to disadvantage its rivals. For example, one strategy is to bid up the auction prices that the rivals have to pay for spectrum. Another is to acquire more spectrum than it actually needs to stop rivals from winning spectrum, anticipating that it can later push up prices to consumers in a less competitive retail mobile market to recoup the initial outlay. Especially for high-stakes billion-pound auctions, it is common for large operators to undertake substantial preparation and engage world-class auction experts to advise them on bid strategies.

- The public, citizens, and mobile consumers do not directly participate in auctions. But a key role of the regulator is to represent their interests, which can be strongly affected by the outcomes that shape levels of industry investment, pace of innovation, strength of downstream competition, extent of network coverage, and the quality and prices of mobile services that consumers receive.

This context means there are important sources of complication in spectrum auctions when compared to auctioning the da Vinci painting. Selling a painting usually has a single objective—to maximise revenue. Spectrum auctions have multiple objectives to be balanced: efficient allocation, competition, coverage, and sometimes also revenue. It is true that, for spectrum auctions, the media often focus on the revenue raised. In the UK the 2000 auction generated exceptionally high revenues for the government of £22.5 billion, while the money raised in the 2013 auction was almost ten times lower at £2.4 billion. Does that make the first a success and the later one a failure? Not at all, because the outcomes in economic welfare for consumers, public value, and the wider economy from spectrum auctions are far larger and much more important than the revenue raised. Auctions designed to maximise revenue can damage efficient allocation and weaken retail competition, leading to more expensive and lower quality services for mobile consumers.

A second key difference is that the da Vinci auction sold a single item to one winning bidder, whereas spectrum auctions usually award multiple blocks of spectrum (or 'lots') to several different winners. The bidders may regard the different lots, to varying degrees, as substitutes for each other ('if we win lot A, we don't need lot B'), or as complements where the whole is worth more than the sum of the parts ('if we win lot C, our value for lot D increases'). These considerations complicate bid strategies because a bidder's value for a lot depends on what else it wins.

A third key difference from art auctions, which can attract a large number of bidders, is that spectrum auctions normally involve only a handful of rival contenders – given that mobile markets tend towards being oligopolies. The small number of operators opens up various strategic opportunities for a bidder to improve its own auction outcome or disadvantage rivals. A further source of complication is that the outcome of the upstream auction for spectrum can also affect the terms of downstream competition and the quality of mobile coverage experienced by the public.

The regulator's fundamental design challenge for the auction is to specify a market process providing self-interested companies competing for spectrum with desirable bidding incentives, so that the auction outcomes achieve the public policy objectives. However, the complications mean there is no perfect design for spectrum auctions to guarantee this. Instead the regulator needs to use judgement about multiple trade-offs in the design decisions. Many interrelated choices have to be made, including the following building blocks:

- Open auctions mean that full information about all bids made in each round is available to all bidders. Closed auctions mean that bidders have no information about the secret bids made by other bidders. In partially open auctions, some but not all information about bids is provided to rival bidders.
- A single lot can be sold per auction, with multiple items perhaps sold in a series of sequential auctions one after the other. Alternatively, an auction can offer multiple lots simultaneously – a simultaneous auction finalises the sale of a lot only after it has identified a winner for all other available lots.
- Auctions can take place with just a single round of bidding (so bidders have a 'one-shot' opportunity only). Or there can be multiple rounds, allowing prices and bidders' demand for the lot(s) to evolve across a series of rounds.
- If there are multiple rounds, there can be ascending prices from one round to the next, such as starting from a low reserve price and continuing to rise until demand from the bidders that are still active matches the available supply. Alternatively, a 'Dutch' auction has descending prices, starting from a high level at which demand from bidders will be below supply and progressively reducing prices across the rounds until the price is low enough that the market clears with the lots sold.
- Bids can take the form of bidders specifying a price for each desired lot. Alternatively, in a 'clock' auction, the auctioneer announces fixed prices in each round and bids are made for the quantities desired at that price. (Despite the name, there is no fixed time limit in a clock auction, and instead the label derives from the large clock face that was used to indicate prices in auctions of tulips in the Netherlands, now displayed electronically).[10]
- Bidders can make individual bids for the lots they want, some of which can win and others lose. Alternatively, in a 'combinatorial' or 'package' auction, bids are for packages of lots which either win or lose in their entirety.
- A winning bidder can pay the price at which it made its winning bid (called a 'pay-as-bid' or 'first-price' rule). Alternatively, with a 'second-price' rule, the price paid by a winning bidder is not set by its own bid but instead by the highest losing bid from another bidder.

These building blocks can be combined in different ways to create many alternative auction formats. Fine art is usually sold in an open, ascending-price, multiple-round auction for a single lot, with bidders making individual bids by specifying a higher price (or responding to the auctioneer's price announcements) to displace the 'standing high bid', and the winner pays the price in its bid (called an 'English' auction).[11] Some spectrum auctions use sealed bids in a single round of bidding, and there are examples with either a single licence being awarded or with multiple lots offered simultaneously; and these contests can involve either individual or package bids and either first- or second-price rules.

More commonly, spectrum auctions are partially open, ascending-price, multiple-round auctions for many lots simultaneously:

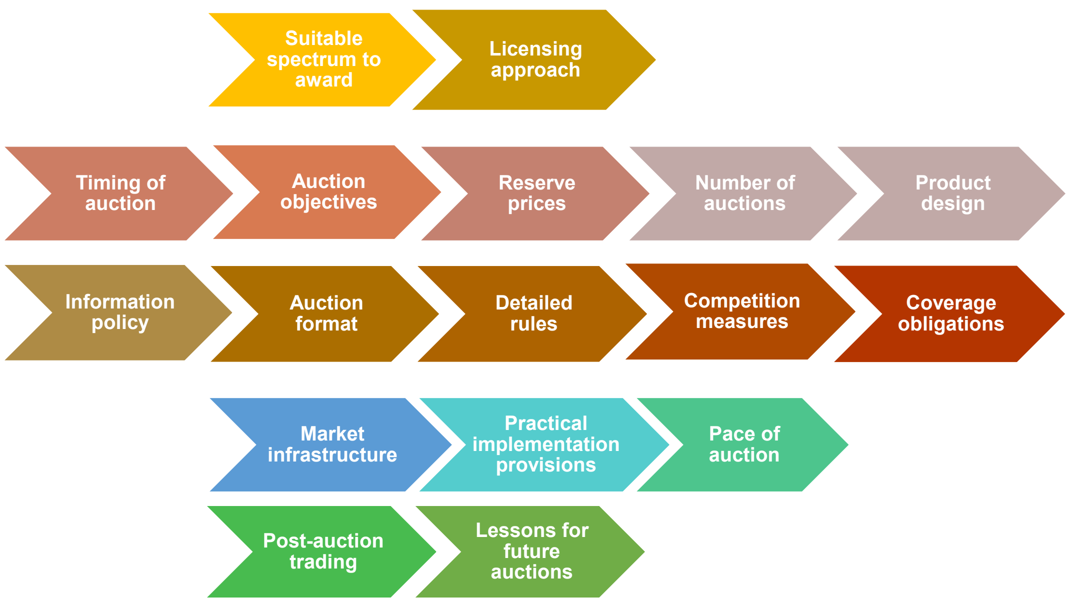
- One of the main formats is the Simultaneous Multiple Round Ascending Auction (SMRA) in which there are individual bids for lots specified in both prices and quantities. A pay-as-bid, first-price rule applies to the winning bids (although in this format it effectively operates similarly to a second-price rule, because a winner only needs to just outbid the highest losing bid).[12]

- The other main format is the Combinatorial Clock Auction (CCA). This is a package auction with two stages, first a clock auction, followed by a single round of sealed bids in which bidders make mutually exclusive bids on as many different packages as they want. However, at most one of these bids can win, and payments by the winning bidders are set according to a second-price rule.

Each auction format is better seen as a family of designs, because many important details affect the ability of bids to fully express companies' spectrum values (which are complicated by interdependencies where lots are substitutes or complements), their incentives for strategic bidding, and the prospects for efficient allocation and revenue. Understanding these considerations and how they are significant in the circumstances of each auction is a key area for expert judgement of trade-offs to decide the specific auction design.

The range of large and small regulatory choices for a fully fledged auction design are illustrated in Figure 2.3, and explored in detail mostly in Part II. Prior steps are in the first row: obtaining suitable spectrum to award, and choosing the licensing approach (Chapter 6). Then there is the question of auction timing and many aspects of designing the auction in the second and third rows: identifying the right objectives, judging the level of reserve prices, deciding the number of auctions, the product design, or granularity of spectrum to be bid for, and the amount of information to be provided to bidders and the public (Chapter 7); choosing the auction format and detailed rules (Chapter 8); assessing the best competition measures (Chapter 9) and coverage obligations (Section 5.3); or harnessing auctions in innovative ways to improve policy choices about them (Chapter 10). The overall

**Figure 2.3. Range of decisions for a spectrum auction**




Source: Author.

characteristics of the auction depend on how all these design elements fit together. After the design decisions, the fourth row shows the regulator's tasks to run the auction, which means providing market infrastructure including an electronic auction platform, and other operational or practical implementation provisions such as auction rooms and security arrangements; and managing the pace of auction bidding. Finally, in the fifth row there are post-auction events of facilitating spectrum swaps or trades between operators, and learning lessons for future auctions (Chapter 11). For all these decisions, across the chapters I draw out analytical frameworks relevant to making well-structured and consistent public policy choices. These frameworks are shown in action for UK auctions and can also be applied to spectrum auctions throughout the world.

## 2.3 Overview of UK auctions


### Summary

- The UK provides an interesting central case study for analysing key issues in spectrum auctions. Four high-stakes auctions offer differing experiences of scale, surprises, and complications, yet within an overall narrative of learning and adapting.
- The UK auctions have been mostly successful through the regulator making auction design choices attuned to the circumstances and imposing well-judged competition measures to promote downstream competition. Varied approaches have been adopted to the important public policy concern of improving mobile coverage.


The UK's experience with spectrum auctions offers insights that are also relevant to other countries for several reasons. The UK regulator, Ofcom, has consistently sought to apply expertise to the auction design choices and adapted to different circumstances. It has been willing to take risks with innovative designs. By contrast, some countries, such as Germany, have stuck with a familiar design. In addition, as a medium-sized and stable liberal democracy, the UK case offers insights into the challenges of decision-making involving multiple public organisations and a range of professional skills.

The UK regulator developed an especially structured and thorough approach to assessing the downstream competition effects of auctions, which guided its choice of proportionate competition measures. The UK mobile market has been amongst the more competitive mobile markets internationally, assisted by consistent and proactive use of measures in spectrum auctions designed to promote strong competition, such as caps on the amount of spectrum that any one operator can hold and more interventionist reservation of spectrum blocks.

Everyone knows the frustration when your mobile service fails to achieve a useable signal in different locations. Operators want to supply busy urban markets, but it is less profitable to invest in new infrastructure in low-traffic areas, for instance, in some rural parts of the country. So improving the extent and quality of mobile coverage is a key public policy concern for regulators and governments worldwide. 'Coverage obligations' on operators offer one way to address this issue, and can be included in spectrum auctions. The UK has taken different approaches over time, illustrating both the advantages and pitfalls of coverage obligations in auctions compared to alternatives – such as governments negotiating with mobile operators to procure coverage directly in hard-to-serve areas.

Figure 2.4 gives an overview of four high-stakes UK auctions used as reference points throughout the book to illustrate concepts and analyse key issues. The heading column shows the auction name and gives a thumbnail description of the outcome. The first column after that shows the date of the auction and the format used for it. The variation in format between auctions reflected conscious choices by the regulator to adapt to circumstances. All the auctions awarded multiple spectrum licences simultaneously, which is important where operators' demand for the lots is interrelated, but the salient aspects of demand were different between auctions:

- The SMRA format for the 2000 auction awarded five licences in one band which were *substitutes*, allowing bidders to switch between them depending on their relative prices in that round in the auction.
- A challenge for the next high-stakes auction in 2013 was that the different coverage and capacity spectrum bands were *complements* for some operators with synergy values, so that the whole was worth more to them than sum of the parts.[13] Accordingly, the regulator chose a different auction format, CCA, with package bids enabling firms to express the complementary value of winning spectrum in both bands. However, package bidding introduces complications, so it comes with disadvantages as well as strengths, such as opportunities for certain types of strategic bidding (e.g. to disadvantage rivals).
- The 2018 and 2021 auctions involved multiple spectrum bands, but there was less evidence of significant synergies in operators' values, which made the simpler SMRA format suitable in both cases.

The second column in Figure 2.4 shows the amount of revenue generated for the UK government by the auctions, which was massively greater in 2000 than in later auctions. The 2000 auction took place at the height of a stock market boom, and at that time the industry had little experience with spectrum auctions either in the UK or internationally, which perhaps contributed to 'overbidding'. In later auctions, bids were less aggressive. Revenue raised by each spectrum auction tends to dominate their media coverage, but compared with other aspects of the outcome (such as economic and social benefits from efficient allocation, strong downstream competition, and improved mobile coverage), the sums raised are much less important.

The third column in Figure 2.4 shows how many winners there were out of the total number of bidders, and the fourth column shows the number of bidding days which reduced across the period. Promoting downstream mobile competition remained an objective of the regulator in all four auctions, and it used a consistent analytical framework. As set out in the penultimate column, the more interventionist policy of reserving some spectrum was used for the 2000 and 2013 auctions (and subsequently vindicated because it supported sustainable competition). However, it was not seen as necessary or proportionate in the 2018 or 2021 auctions, which used only spectrum caps. The final column in Figure 2.4 indicates coverage obligations that were attached to some of the auctioned spectrum licences. Such provisions can contribute to operators extending mobile coverage. But they are far from problem-free, running the risk of overpromising and under-delivering for consumers. Alternative policy approaches can be adopted, and over time the UK government has moved more

**Figure 2.4. Summary information on high-stakes UK auctions**

| Auction name, description | Year and auction format | Revenue in £ billion | Number of winners (and bidders) | Number of bidding days | Competition measures | Coverage obligations |
|---|---|---|---|---|---|---|
| **3G auction:** 'Biggest auction ever' | 2000 SMRA | 22.5 | 5 (of 13) | 36 | Reservation for a new entrant<br>Maximum of 1 licence per bidder | All 5 licences required 80% population coverage by the end of 2007 |
| **4G auction:** 'Surprises and complications' | 2013 CCA | 2.4 | 5 (of 7) | 14 | Flexible reservation<br>2 spectrum caps | 1 licence: 98% of premises indoors by the end of 2017 |
| **PSSR auction:** 'Widely seen as successful' | 2018 SMRA | 1.4 | 4 (of 5) | 10 | 2 spectrum caps | n/a |
| **5G auction:** 'Short and sweet?' | 2021 SMRA | 1.4 | 4 (of 4) | 3 | 1 spectrum cap | Superseded by a government agreement with the operators |

Source: Author from National Audit Office (2001) and Ofcom auction documents.
Notes: SMRA: Simultaneous Multiple Round Ascending Auction; CCA: Combinatorial Clock Auction; PSSR: Public Sector Spectrum Release (because the 2018 auction spectrum was released by the Ministry of Defence).

towards direct procurement from mobile operators as a way of improving coverage. In the remainder of the section I give a brief account of each of the four UK auctions (see Section 11.1 and Annex A for further details).

### 3G auction in 2000: the 'biggest auction ever'

The UK's first spectrum auction was a humdinger. Assisted by heavy pre-auction marketing, there was an unusually large number of bidders leading to very strong competition in the auction, a lengthy bidding duration of 36 days, and extremely high prices. The auction raised revenue from licence sales of £22.5 billion, which was 45 times larger than the reserve prices set at £500 million (and an order of magnitude larger than the official pre-auction revenue forecast of £1–3 billion). Four of the five eventual winners in the auction were the incumbent national mobile operators (at the time BT, One2One, Orange, and Vodafone). The last winner, H3G, was victorious after out-competing eight rival bidders for the 'set-aside' spectrum licence reserved for a new entrant.

There are several explanations for the startlingly high and never-repeated revenue. At the height of a telecommunications stock market boom, the prospects for new market entry seemed especially bright, and incumbent firms were convinced that their future viability depended on winning a 3G spectrum licence. A 'winner's curse' effect may have been fuelled by stock market expectations, fear of losing, and managerial overconfidence about the commercial prospects of 3G which was regarded by some at the time as heralding a new world of mobile internet. The industry and bidders were also less experienced with auctions. Observers were amazed as prices continued to go up and up to become the highest-revenue auction then ever seen in history. News reports referred to 'staggering sums of money'.[14]

In assessing the outcome we should distinguish between the allocation to the winners which looks economically efficient, and the prices paid which seem to have resulted from overbidding. With the benefit of hindsight we can see that 3G did not lead to such a large step-change in mobile services, and Peter Bonfield, BT's chief executive, later said that the industry 'spent £10 billion too much'.[15] After the telecommunications stock market boom, the bust followed on the tails of this auction. Bidders learned lessons from their mistakes in the UK's 3G auction and the similarly high prices in Germany's 3G auction later in 2000, and governments gained much lower revenues in later auctions, both in the UK and in most overseas sales.

The 2000 auction was a clear success in reserving spectrum for a new entrant. The beneficial boost to downstream mobile competition has been long-lived. While H3G (using 'Three' as its brand name) remained the smallest operator throughout the two decades since the 2000 auction, it was also an important competitive force. H3G was the first network to launch 3G services in the UK after the auction, choosing to do so symbolically on 3/3/2003.

All five licences in 2000 contained an obligation on operators to achieve 80 per cent population coverage of 3G services, and ensure wide rollout of the new technology. However, the requirement fell between two stools. On the one hand, it turned out to be more challenging than expected for operators to meet, due to the move from stock market boom to bust and commercial incentives for slower 3G rollout. Some operators struggled and may have distorted their network rollout in order to meet the obligation. To use a pizza analogy, they may have provided 'thin and crispy' coverage that just met the defined requirements of the specific obligation, but offered less meaningful services to consumers than better quality 'deep pan' coverage. On the other hand, the 80 per cent reach was insufficient to assuage public concerns because it remained a long way from achieving even near-universal mobile coverage. The government later increased the requirement to 90 per cent population coverage in 2010, as part of a wider deal with the operators.

While the operators learned salutary lessons about avoiding overbidding in future, the learnings for the regulator were more fine-grained. The auction design provided bidders with an 'all or nothing' choice, as each was permitted to bid for only one pre-packaged licence in any round. The regulator drew the lesson that greater flexibility for bidders would be more important in later auctions when operators would already have larger spectrum portfolios and more diverse requirements to add new spectrum. Another regulatory lesson was the success of the competition measures, including spectrum reservation for a new entrant. Experience with the coverage requirements was more chequered, suggesting that it did not provide a simple solution to coverage concerns.

## 4G auction in 2013: surprises and complications

Various smaller auctions of less valuable spectrum occurred in intervening years, but the next high-stakes auction in the UK was not until 2013, when key bands for 4G services became available. One operator, EE, already had spectrum holdings suitable for early 4G – EE had been created in 2010 by a merger of previously separate operators, Orange and T-Mobile (formerly One-to-One). The other three remaining incumbents needed spectrum from the 2013 auction: these were now Vodafone, H3G, and Telefónica (which had bought BT's mobile operations).

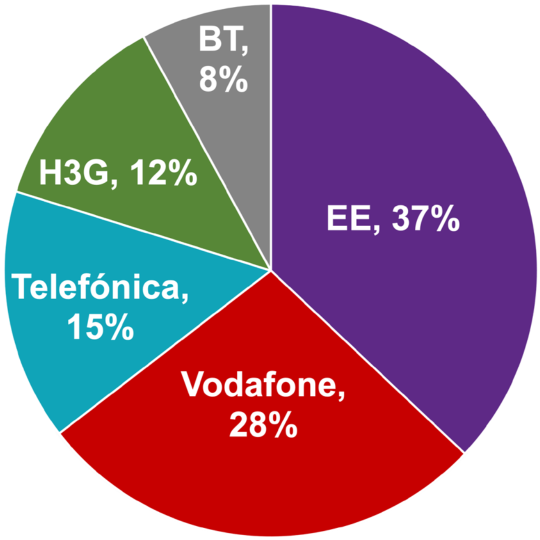
The regulator expected operators to have synergy values between the coverage and capacity spectrum in the auction. It also considered it was appropriate to use flexible spectrum reservation, a technique using 'spectrum floors' where auctions bids determined the particular frequencies to be reserved, instead of pre-specified set-aside spectrum. So Ofcom chose a complex and innovative CCA design, with 'bells and whistles' designed to fit the circumstances. These complications had a purpose but they worried operators. Some auction features worked, and others did not, but overall the auction managed 'not [to] topple over under the weight of its own complexities'.[16]

Most media reporting focused on the shortfall between the revenue of £2.4 billion and the pre-auction forecast of £3.5 billion made by the UK's independent Office of Budget Responsibility. Some commentary also made unrealistic comparisons to the £22.5 billion raised in 2000. However, it was appropriate that the 2013 auction was designed to maximise economic efficiency and public value rather than revenue. The bidding by operators was rational and reasonably competitive – for instance, the total prices were bid up to a billion pounds higher than the reserve prices of £1.4 billion. Three bidders without existing mobile spectrum joined the four incumbents as bidders. The biggest of these was BT, the dominant landline provider (and former state monopoly privatised in 1984). After spinning off its mobile arm a decade before in 2002, BT was once more interested in running mobile operations. The company was successful in the auction, perhaps surprisingly outbidding mobile incumbents for a portion of the capacity spectrum. The remaining lots were all won by incumbents, so that there were five winners in the auction. Two smaller operators (Hong Kong Telecom and MLL) participated, but were unsuccessful.

Some other aspects of the bidding and outcome were also unexpected. EE chose to bid much more aggressively at the margin for capacity spectrum than for coverage spectrum, and won a surprisingly large proportion of the capacity spectrum in the auction. By contrast, it won only a small amount of coverage spectrum, even though it had little pre-existing coverage spectrum in its portfolio. The choice of spectrum floor as the reserved spectrum was between a small amount of valuable coverage spectrum and a larger but less valuable block of capacity spectrum. Unexpectedly, the pattern of bids made by both H3G, the beneficiary of reservation in practice, and other bidders led to the higher-value coverage spectrum being determined as H3G's winning floor of reserved spectrum. Overall, the efficiency of the spectrum allocation that was achieved was hard to judge, because of conflicting indications. For example, the CCA auction format helpfully allowed bidders to express their synergy values, but it also made bidding more difficult for those operators with tight budget constraints.

The spectrum caps did their job but still permitted significant asymmetry in spectrum holdings – see Figure 2.5. There were subsequent ramifications, e.g. Telefónica, with only 15 per cent of total spectrum despite having more than 30 per cent of subscribers, became the largest winner of spectrum in the next auction in 2018.[17] The other main competition measure in 2013 of flexible reservation either for the smallest incumbent H3G or for a new entrant was contentious, both because it was interventionist and for the innovation of spectrum floors. Operators threatened to sue Ofcom in the courts but this was avoided, in part because the government reached a wider agreement with operators on a package of measures that included the 2010 increase in 3G obligation. Spectrum floors were subject to strategic bidding by H3G, but still seemed consistent with an efficient outcome (see Section 10.1 for details).

**Figure 2.5. The UK operators' shares of spectrum after the 2013 auction**




Source: Author from Ofom auction documents.

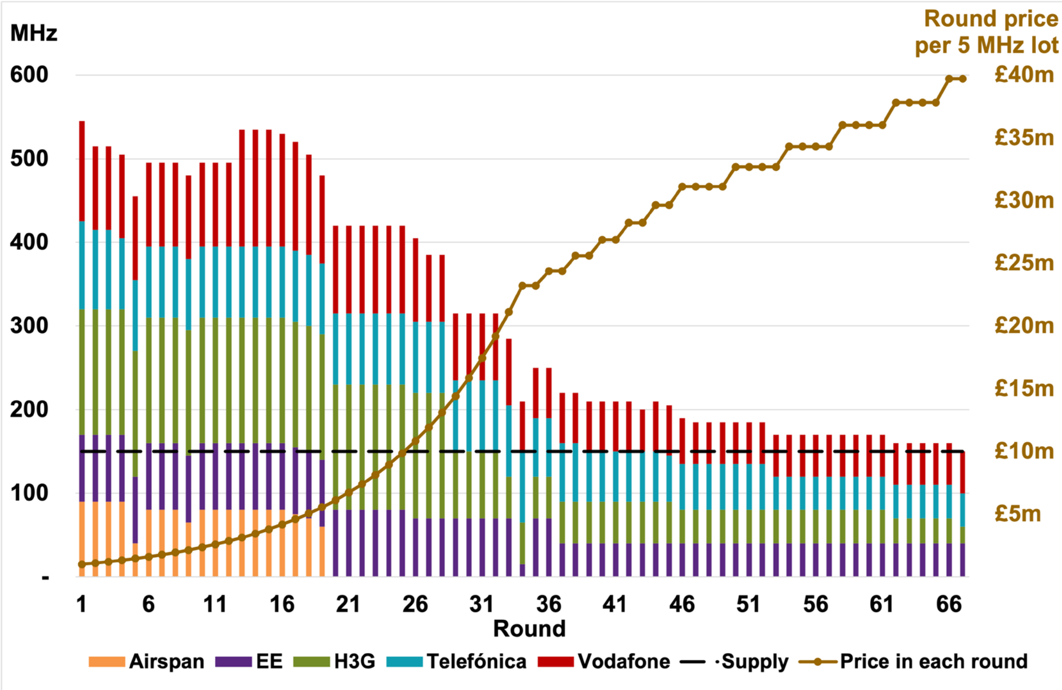
Turning to coverage requirements, an obligation requiring the operator to achieve 98 per cent indoor 4G coverage was applied to one licence, on the rationale that it would speed up rollout across the country and stimulate other operators to follow. The practical outcome was more complex, because that apparently simple headline masked substantial engineering complications in the detailed specification of the obligation. Telefónica won the obligation spectrum, but achieved lower coverage than intended on the ground, 95 per cent in 2018. Other operators achieved indoor coverage of 94, 89, and 88 per cent.[18]

Thus, as in 2000, competition measures were successful, and experience with the coverage obligation was messy. The complications in the auction design had mixed success, and the efficiency of the spectrum allocation was inconclusive. This outcome highlights that design innovations carry a two-sided risk. On the one hand, innovation can reap a reward from harnessing the auction to achieve desirable outcomes. But care is also needed to deploy 'heavy machinery' features only when they truly fit the circumstances.

## PSSR auction in 2018: widely seen as successful

The spectrum in the 2018 auction was released by the Ministry of Defence after it shifted its relevant operations to alternative spectrum. One band in the auction was for 4G capacity, and another was prime 5G spectrum. In this case there were no strong synergies between the bands (which were both

**Figure 2.6. Bids for the 5G spectrum band in the 2018 auction**




Source: Author from Ofcom auction documents.

capacity spectrum), so Ofcom concluded that the complications of the CCA format were not needed. Instead a simpler design was used, the SMRA. The auction went very well, especially for 5G spectrum. Figure 2.6 shows the bids and prices in each of the 67 rounds of bidding for that band. There were initially five bidders, four incumbents (EE, H3G, Telefónica, and Vodafone) plus a potential entrant, Airspan. They all initially bid for large amounts of spectrum (totalling more than 500 MHz) at the reserve price of £1 million per 5 MHz lot. As demand was in excess of the available supply of 150 MHz, Ofcom increased the price in the next rounds. As prices continued to rise, the incumbents broadly maintained their demand until Airspan dropped out of the bidding at the higher price of £6.1 million per 5 MHz in round 20. The four incumbents then progressively reduced the number of lots they were bidding for as prices continued to rise until they all won spectrum blocks, generating £1.2 billion in revenues for the government (30 lots at the final price of nearly £40 million per lot). Simultaneously there was also bidding for the other band in the auction where Telefónica acquired the 4G spectrum to alleviate concerns about its network capacity constraints, adding another £0.2 billion to the revenue raised.

The most contentious aspect for this auction was Ofcom's imposition of spectrum caps, which led to pre-auction litigation and a 4-month delay before the all-clear to proceed. EE had been taken over by BT in 2016, combining their spectrum portfolios (but retaining EE as the brand name). One cap prevented EE from bidding for the 4G spectrum – to prevent it increasing its already large pre-existing holdings. The other cap limited EE's acquisitions of 5G spectrum. Although the latter did not turn out to be a binding constraint when the auction took place, EE's earlier legal appeal had claimed it was too restrictive. At the same time H3G mounted a legal appeal claiming the opposite, that the limit on EE was too lax. The regulator won both cases at the High Court and Court of Appeal, reinforcing the robustness of its competition analysis and decisions.

Once the auction started, it went smoothly, and the outcome satisfied the operators. It was also a good result for economic efficiency and promoting competition, and so was widely seen as successful. Telefónica won the 4G spectrum allowing it to provide better 4G services to its customers. All four operators launched their 5G services promptly enough in 2019. Because this auction awarded only capacity and not coverage spectrum, there were no coverage obligations in the spectrum licences awarded. The auction's success emphasised the benefits of a horses-for-courses approach to design choices, since the less complicated SMRA design was well suited to the prevailing conditions and met the regulator's objectives very effectively.

## 5G auction in 2021: short and sweet?

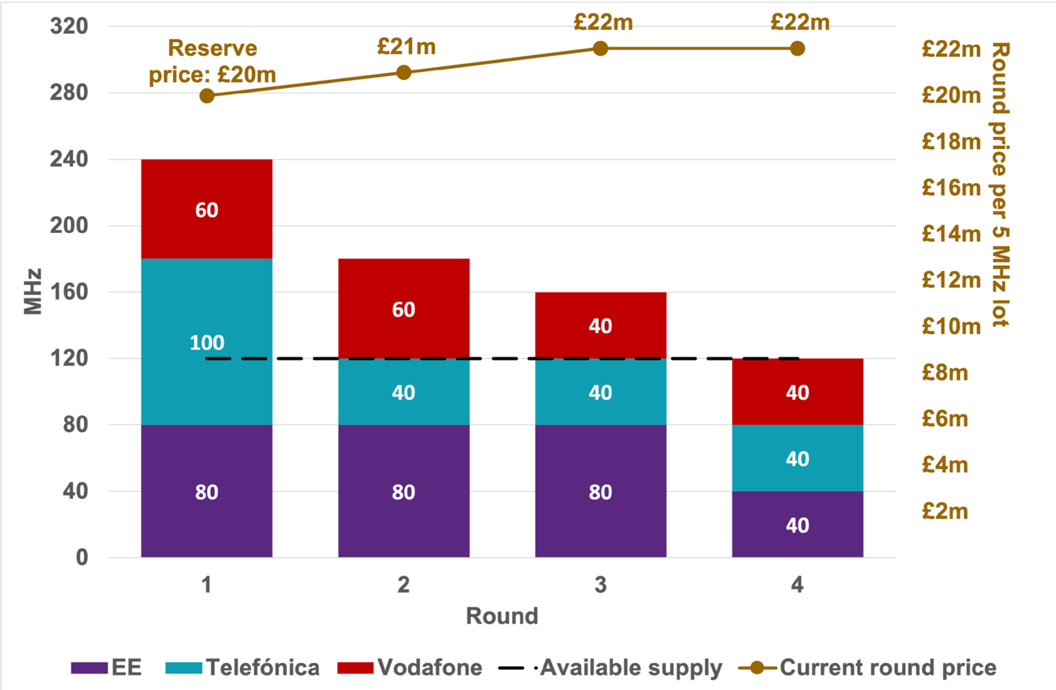
The next 5G auction awarded both coverage and capacity spectrum bands. It was due to happen in 2020 but was delayed by the Covid-19 pandemic, eventually taking place in 2021. It used a very similar SMRA design as in 2018. Bidding by the companies was starkly different, however, and far less competitive, lasting only 11 rounds for coverage spectrum and just 4 rounds of apparent tacit collusion for the capacity band as Figure 2.7 shows.

Only three incumbents bid for the 5G capacity band. H3G already held a large amount of 5G capacity spectrum and chose not to bid for more. The other firms initially bid for different amounts, but then took it in turns to reduce their demand to the 'focal' amount of 40 MHz each, in order to split the spectrum equally between them at a low price that was only just above the reserve level. The revenue generated by sales of this band was £0.5 billion (24 lots at £21–22 million per 5 MHz lot). The price was 45 per cent lower than for the very similar 5G spectrum sold in the 2018 auction. Such strategic bidding to win cheap spectrum is called 'market division', and one weakness of the SMRA format is that it is more vulnerable to such oligopolistic and concerted behaviour.

There was a little more competition in the bidding for the coverage band between all four operators (but no potential entrant participated in the 2021 auction). Vodafone dropped out in round 11, leaving the other three – EE, H3G, and Telefónica – to win equal amounts still at a relatively low price compared to benchmarks from European countries. Because the government had reached an agreement on coverage extension with operators the previous year (see Section 5.3), no coverage obligations were needed in the auction.

Assessing the success or failure of the 2021 auction differs depending on the view taken of the objectives. The desirability of the outcome was very questionable for those seeing revenue as an important objective, because total revenue was only £1.4 billion. That was the same as for the 2018 auction, but greater revenue might have been expected due to the valuable coverage spectrum included in the 2021 auction. However, revenue-raising was not part of the regulator's objectives. For efficient allocation and promoting downstream competition, which are usually more important than revenue, the auction had the advantage of being short and sweet. Despite the tacitly collusive bidding for the capacity band, the outcome plausibly achieved an economically efficient allocation, which was also desirable for vibrant downstream competition. This is because two operators that had less coverage spectrum (EE and H3G) increased their amounts, and all four of them achieved large holdings of 5G

**Figure 2.7. Bids for the 5G capacity band in the 2021 auction**




Source: Author from Ofcom auction documents.
Note: The numbers inside the column bars show the amount of each operator's MHz bid in that round, with only 120 MHz available.

capacity spectrum, thereby attaining strengthened spectrum portfolios to offer enhanced 5G services to consumers.

One key lesson from this experience for the regulator was that using the same design in different auctions provides no guarantee of similar bidding patterns. Both the 2018 and 2021 auctions used an SMRA design, but the contrast in operators' bidding behaviours was stark, as illustrated by the very large difference in bid patterns between Figures 2.6 and 2.7 for very similar 5G spectrum. The 2021 experience also emphasised that there are different ways to achieve desirable outcomes. Strong competition in the auction as in 2018 provides a far more secure route than self-interested operators exploiting weak bidding competition as in 2021. Ultimately, however, the competitiveness of auction bidding is only a means to the more important ends of promoting economic efficiency and downstream competition.

Overall, across all four auctions the UK experience has been mostly successful, especially through well-judged design decisions, learning over time, adjusting as conditions change, and active use of proportionate competition measures. Having provided in this chapter an introductory understanding of radio spectrum and auctions, and an overview of UK auctions, we are now in a position to explore the design decisions in greater detail. The next chapter starts by providing the conceptual underpinnings of auction design analysis.

## Notes

[1] A Hertz is defined as one wave per second. Other technical dimensions include transmission power in Watts and signal strength in decibels.

[2] Based on Ofcom (2008b, figure 2.53).

[3] Competition and Markets Authority (2015).

[4] For more, see: Wikipedia 'GSM frequency bands', https://perma.cc/V58E-QV8L.

[5] For historical accounts of spectrum management in the USA and arguments favouring auctions, see Kwerel and Felker (1985).

[6] See Indian Premier League 'TATA IPL Auction – 2022', https://perma.cc/X6CK-PD9P.

[7] See Financial Times 'Economist develops UK subsidy auction to save endangered turtle dove', 23 July 2021, https://www.ft.com/content/6bfbd5e2-10f9-4400-b4e1-258225e3ac0f

[8] See Guinness World Records 'Most expensive painting sold at auction', https://perma.cc/AUC8-9GJC.

[9] Nobel Prize (2020a).

[10] See Amsterdam Tulip Museum 'Dutch Clock Auctions', https://perma.cc/D2UZ-FFX8.

[11] Ashenfelter (1989).

[12] The description here of the SMRA pricing rule as first-price or pay-as-bid reflects common colloquial practice, but is non-standard in the auction theory literature, especially given the functional similarity to second price. In the literature, a 'first-price auction' usually refers to sealed bids for a single unit; and a 'pay-as-bid auction' to sealed bids for multiple homogeneous goods, such as for Treasury bills, in which winners pay different (non-uniform) prices according to their bids (also known as a 'discriminatory auction').

[13] A numerical example (using EE's real bids in the 2013 auction in £ million) is values of: 230 for one lot of 800 MHz; 697 for seven lots of 2.6 GHz; and 1,050 for the combined package (one lot of 800 MHz plus seven lots of 2.6 GHz) which was EE's winning bid in the auction. The synergy is 123, the excess of 1,050 over the sum of the values for the two smaller, single-band packages (see also Figure B1.5).

[14] See BBC News 'Looking back at 3G auction in 2000', https://www.bbc.co.uk/news/av/technology-21522129.

[15] From an interview with the Sunday Times – see French (2009, p.166).

[16] Cave and Nicholls (2017, p.377).

[17] Ofcom (2017, figure A1.17b).

[18] Ofcom (2018c, figure 6).

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Note: 🔓 means an open access publication.


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