Access to spectrum and valuation of spectrum for private LTE

April 2018

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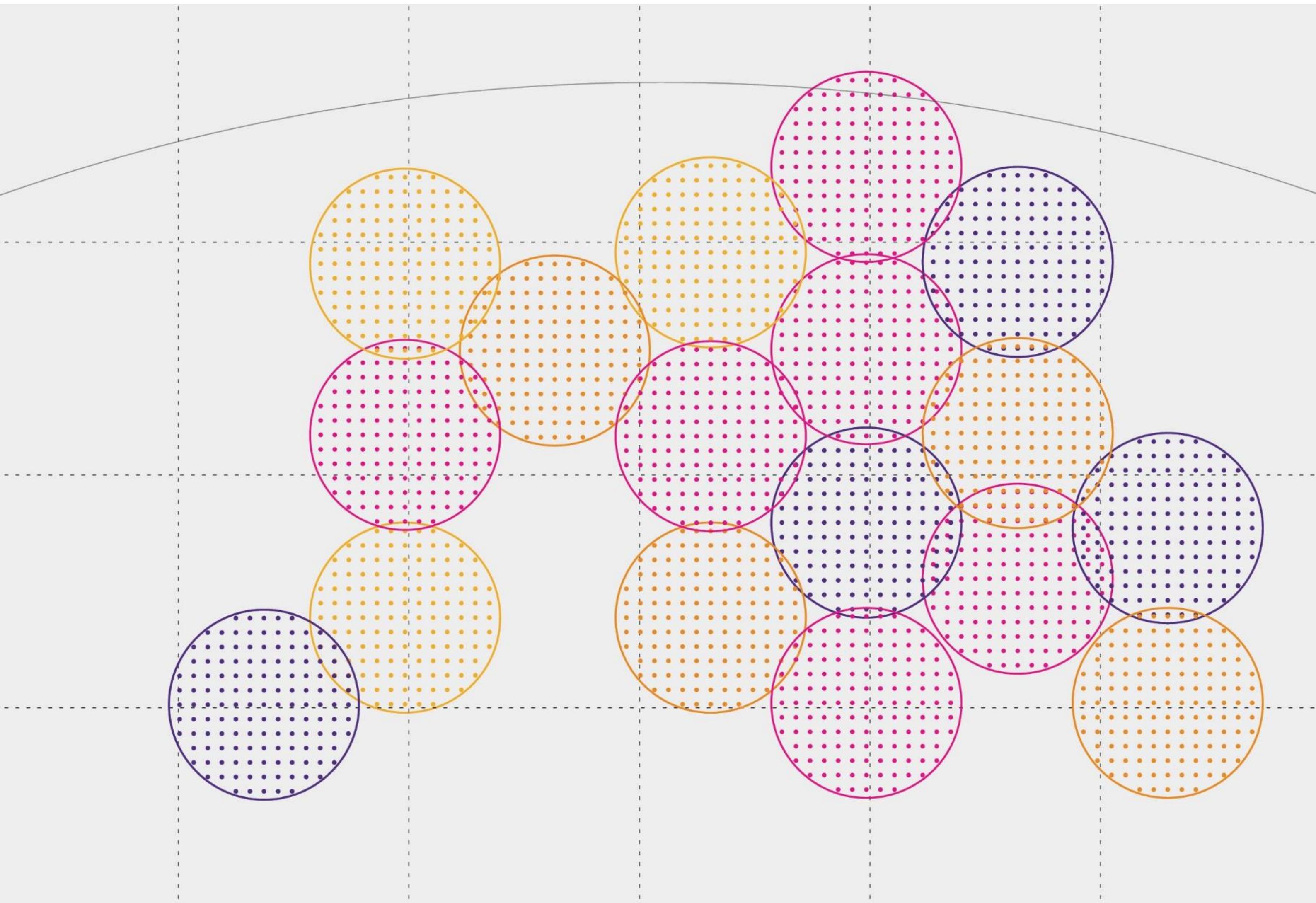


About Plum

Plum is an independent consulting firm, focused on the telecommunications, media, technology, and adjacent sectors. We apply extensive industry knowledge, consulting experience, and rigorous analysis to address challenges and opportunities across regulatory, radio spectrum, economic, commercial, and technology domains.

About this study

This study considers spectrum access mechanisms and the valuation of spectrum for private LTE. It considers changes required to current practice for mobile spectrum bands and makes recommendations for policy makers or regulators.

Contents

1 Introduction

This research study addresses how spectrum could be valued for private LTE. While the principles for valuation may be the same as those used by regulators and mobile operators in mobile spectrum awards, the context for private LTE differs in three important respects.

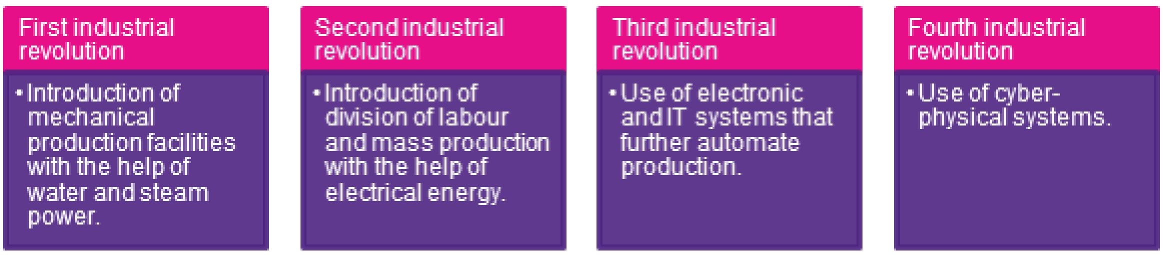
- The localised nature of private LTE is very different from the mostly dedicated national use of spectrum by mobile operators.
- Second, the business case of a private LTE operator is different from the business case of a mobile network operator.
- There could be many private LTE operators should the market develop. This potentially creates a more fragmented environment.

This report follows on from research undertaken by Plum in its initial report on private LTE.[1] The scope and outputs of that report are summarised below by way of introduction to the material in this report.

1.1 Scope and key points of the first report

Plum's first research report on "Use cases and spectrum requirements for private LTE" considered enablers, framers and opportunities for private LTE. Its focus was on industrial automation – a less high profile vertical than some others such as automotive but still of great importance to economic and social wellbeing. Industrial automation is advancing rapidly with the full integration of electronic communications and other digital technology into industrial equipment and processes. These integrated systems are often referred to as cyber-physical systems. In this context there is often reference to "industry 4.0". This is illustrated below.

Figure 1: "Industry 4.0"



Two megatrends increasingly seen in industrial automation are use of robots and drones. In addition, Virtual Reality (VR) and Augmented Reality (AR) are allowing further development of industrial automation, including the ability to simulate a user's presence in an industrial situation and/or presenting a view of a physical real-world environment enhanced by audio, video and graphics. These developments, which could require significant levels of bandwidth and quality of service delivered

[1] Use cases and spectrum requirements for private LTE. A research report. November 2017

through private networks, could open many new opportunities for interaction and control and deliver further efficiency gains.

Key to enabling private LTE is access to suitable harmonised spectrum on terms that fit with the business case for private communications applications. In the previous report spectrum requirements for applications were characterised, options for providing access to spectrum considered (including the use of licence exempt spectrum with technologies that enable LTE, like LTE-U and MuLTEFire) and a review carried out of the mechanisms for access to spectrum in several countries. The use of wholesale networks as a means of supporting private LTE was also considered.

One of our key findings was that there is currently little possibility of access to harmonised spectrum already awarded to mobile network operators. Also, there seems to be little consideration by regulators and spectrum management authorities of the need to think of private LTE when awarding spectrum in future. This leaves those wanting to operate private LTE with the choice of using licence exempt spectrum (which may not deliver sufficient quality of service), or leasing/sharing spectrum with licensed mobile operators.

- In harmonised mobile bands, shared access to spectrum is still largely the exception rather than the norm. Mechanisms such as CBRS in the United States and possibly LSA in Europe may provide a model for future spectrum sharing that could be used by private LTE but it is too early to form a clear view on the extent to which this may be possible.

- In many places, transfer of spectrum via spectrum trading/leasing is possible but it is often hard to gauge what can really be done. There is a lack of clarity about the nature of transfers that are allowed. For mobile spectrum, there is also an assumption that spectrum would be transferred on a national basis between mobile operators rather than at specific locations to a private LTE provider.

In summary, there is a far from uniform picture for the operation of spectrum trading/leasing even where there is the ability to do so (such as in EU Member States).

Time to access spectrum is an important consideration for setting up private LTE. There will inevitably be a trade-off between what may be the ideal band(s) for a given case and what in practice can be achieved. Underutilised bands could be an opportunity for private LTE (such as 2.3 GHz and 2.6 GHz TDD). These bands provide a good balance between coverage and capacity and to date have not been widely used in many places. The 3.4-3.8 GHz band and possibly in future the 3.8-4.2 GHz band and mmWave spectrum could be attractive options for private LTE. However, it will be necessary to influence regulatory thinking as there is already movement on awarding spectrum in the 3.4-3.8 GHz frequency range along traditional lines.

1.2 Conclusions of the first report

The conclusions and recommendations from the first report are set out below.

1.2.1 Previous conclusions

- There is ongoing scope for the development of private LTE network solutions for industrial automation. The move to cyber-physical systems and the convergence of platforms facilitated by LTE technology is a key enabler for this.
- The technology for private LTE will be available in the short term and it will access the scale and scope benefits of LTE, its ecosystem and its evolution to 5G.
- A range of implementation solutions is possible, ranging from stand alone to hosting on a public mobile network or a dedicated wholesale network, which will provide flexibility of options for implementation.
- Key to the success of private LTE solutions is the ability to access suitable harmonised mobile spectrum in required locations, in in a timely way and on appropriate terms. This is likely to be challenging given the current approach to assignment of this spectrum, the lack of active secondary spectrum markets and the very limited use of spectrum sharing in these bands.

1.2.2 Previous recommendations

1. Governments and regulators should expand their view of the use of mobile systems to include provision of private network services and in particular private LTE. The private LTE concept is an enabler for industrial automation and it is realisable now.
2. The roll out of private LTE is constrained by an inability to access harmonised mobile spectrum. Authorisation of this spectrum is required on a localised basis and not the national/dedicated basis that has applied to date for mobile network operators providing services to the public. Governments and regulators should consider the following mechanisms for accessing mobile spectrum on a localised basis:
    a. Spectrum transfer through trading and leasing (the latter being likely to be more applicable to private LTE).
    b. Spectrum sharing concepts that deliver guaranteed quality of service such as Licensed Shared Access (LSA).

1.3 Valuation

The first report considered technical and procedural issues for access to spectrum for private LTE services. However, it left a critical question unanswered, which is the valuation of this spectrum. There are key differences between the approach used for valuing spectrum from the perspective of a mobile operator and that of a private LTE operator. Even in the case where spectrum is potentially available to share or lease, if there are incompatible views on valuation, private LTE operators may still be unable to gain access, which could inhibit development of private LTE. This report addresses the spectrum valuation question for private LTE.

1.4 Structure of the report

The remainder of this report is structured as follows:

- Section 2 considers spectrum management aspects.
- Section 3 discusses methods for valuing spectrum.
- Section 4 looks at valuation of spectrum for private LTE.
- Section 5 provides a benchmarking analysis of two key spectrum bands for private LTE.
- Section 6 considers other policy and regulation issues for private LTE.
- Section 7 presents our conclusions.

2 Spectrum management aspects

The fundamental rationale for spectrum management is the need to avoid interference between users in adjacent frequencies or across geographic borders. Hence access to radio spectrum has historically been tightly regulated. The framework for spectrum use is set out in the ITU Radio Regulations and allocations can be either on an exclusive or shared basis (primary or secondary status). Decisions on the Radio Regulations which are made at World Radiocommunication Conferences (WRC) are then reflected in the national frequency allocation tables by each national administration which is responsible for managing national spectrum use.

2.1 Spectrum licensing

Access to spectrum is traditionally based on licensing by relevant spectrum management authorities. The licence conditions will typically include technical requirements on usage, equipment and technology interfaces and there may also be other additional conditions depending on the nature of the use (e.g. coverage obligations for public networks). Spectrum licences can be classified into two broad categories, apparatus[2] licences and block licences. In general, both types of licences provide dedicated use of the licensed frequencies with limited scope for sharing.

2.1.1 Apparatus licence

The apparatus licence involves licensing on an equipment or transmitter basis with technical coordination done by the regulator. This is commonly used for fixed links, land mobile (private mobile radio) and satellite earth stations. These are used for a range of services including aeronautical, amateur radio, fixed, land mobile, maritime and radiodetermination. While apparatus assignments were sometimes used during the early years of cellular mobile, these have generally been phased out by regulators around the world in favour of block assignments.

2.1.2 Block licence

The block assignment approach involves licensing of a block of spectrum on an area-defined basis which allows multiple transmitting stations to be deployed provided certain technical conditions, such as specified field strength, are met. This is common for cellular mobile and in some cases fixed links in higher frequency bands, such as bands above 20 GHz.

Block assignment for cellular mobile is considered the best practice given the nature of spectrum use. First, this reduces the administrative burden for the regulator as it avoids having to issue licences for every single transmitter utilising the spectrum in question. Second, and more importantly, charging licence fees on a per transmitter basis has the opposite effect of promoting efficient spectrum use and improving coverage through network expansion. For the same bandwidth assigned, an operator that

[2] Sometimes known as transmitter, station or technical licences.

has a larger and denser network would have to pay more than one that has rolled out fewer base stations.

In the case of public cellular mobile, licences have tended to be on a national basis given economies of scale and network effects although some regional licences may be used in geographically larger countries or in higher frequency bands. For private LTE, deployments are likely to be on a small scale at specific locations, which means national block are unlikely to be appropriate.

2.1.3 Licence exempt

A third approach is licence-exempt spectrum access, also known as the commons approach. Unlike traditional command-and-control licensing, this approach allows anyone to use certain frequency bands so long as they comply with rules designed to avoid or limit interference with other users in the same band. Common uses of licence-exempt spectrum include Wi-Fi, Bluetooth, cordless phones and near-field communication (NFC).

2.2 Assignments methods

There are different methods employed by regulators to assign spectrum and these will vary depending on the type of applications and the nature of demand. For public cellular mobile, the most common assignment approaches are auctions and beauty contests.

2.2.1 Auctions

Auctions are widely used for the assignment of spectrum for which there is excess demand, particularly public mobile spectrum. They have the advantage of being more transparent and efficient than alternative methods such as beauty contests or direct awards. A well-designed auction provides incentives for bidders to bid according to their valuation and ensures that the bidder with the highest valuation, and thus the one most likely to make the most efficient use of the spectrum, obtains the spectrum resource.[3]

An auction is a market-based approach to the assignment of spectrum and delivers an economically desirable outcome although other considerations such as competition and social factors may need to be considered as part of the auction design. For example, spectrum caps and set-asides are commonly used to ensure there is effective competition among operators in the market.

2.2.2 Beauty contests

Beauty contests tend to be used when there is a strong emphasis on non-economic policy objectives. Potential licensees are evaluated according to specific criteria identified by the regulatory authority. These can include factors such as coverage levels, rollout timescales, quality of service, new services,

[3] Radio Spectrum Policy Group. RSPG Report on Efficient Awards and Efficient Use of Spectrum. RSPG16-004. 24 February 2016.

prices and bidder's financial standing and track record. The spectrum would then be awarded to those who score best on the set criteria.

While beauty contests provide more control and flexibility to regulators, there is a trade-off in terms of economic efficiency. In addition, the evaluation criteria can be subjective, and the evaluation process is not always transparent. There is a higher risk of disputes and legal challenges associated with beauty contests.

2.2.3 Direct awards

Direct administrative award is a common practice, particularly where scarcity or excess demand is not expected. These can be done on a 'first-come first-served' basis once the licence is made available by the regulator. This approach is common for spectrum used by many service types (fixed links, earth stations, private mobile radio) for which excess demand is not likely. Renewals or re-assignments are, by definition, direct awards. This approach is simple to administer and minimises regulatory costs although it may not always lead to efficient allocation of spectrum in situations of scarcity.

Figure 2.1 provides a comparison of the strengths and weaknesses of the different assignment methods, the risks associated with each of them and the situations where their use is considered most appropriate. Hybrid approaches that combine elements of all three methods are possible. For example, in France the 800 MHz and 2600 MHz awards in 2011 involved a sealed bid single round auction and a beauty contest evaluation process based on coverage and MVNO hosting commitments made by the bidders.[4] In Hong Kong, the renewal of the 2100 MHz band in 2014 involved a combination of direct award and auction for different parts of the band.[5]

Figure 2.1: Comparison of assignment methods

	Auction	Beauty contest	Direct award
Strengths	Results in allocative efficiency (economic terms). Can be simple. Transparent. Returns economic value to the government and society.	Focus on quality. Thorough procedure. Regulator retains (most) control over the assignment.	Simple and quick process. Regulator retains complete control over assignment. Provides certainty in case of renewals.

[4] Information on the France auctions can be found [here] and [here].
[5] Information on the Hong Kong auction can be found [here].

	Auction	Beauty contest	Direct award
Weaknesses	Regulator has less control over outcome. Auction payments tend to be an upfront investment and may slow down service investments due to capital market constraints.	Do not necessarily maximise economic efficiency. Time consuming. Not transparent. Selection of who should be on the judging panel may unduly influence results.	Lack of transparency. Likelihood of inefficient outcome if demand exceeds supply. Susceptible to regulatory capture. Regulators set prices which may be excessive.
Risks	Collusion between bidders could result in lower proceeds. Errors in the auction design and execution could result in inefficient outcomes. Winner's Curse (winning bid exceeds asset value).	Risk of appeal procedures. Can result in excessive profits for licence holder (regulator sets price too low). Operators may be unable to meet the promises made. Winners' Curse.	Risk of appeal procedures. Expropriation risks and "hold up" problem may lead to adverse outcomes.
Situations in which use is appropriate	The supply of frequencies to be assigned is less than the demand. Quality requirements can be formulated upfront. There are no market distortions that could jeopardize long-term interest of end-users.	The number of licences is limited. Control over assignment process is necessary (e.g. in highly distorted markets). Supplementary requirements are needed based on social and cultural factors (and need to be compared).	There is no excess demand for spectrum being awarded. Might be suitable in certain renewal cases where increased certainty is aligned with policy objectives (e.g. minimising service disruption, promoting investment).

2.3 Sharing approaches

Spectrum sharing has been around for a long time. In recent years there has been renewed interest in spectrum sharing as demand for spectrum, particularly to support mobile broadband services, has grown rapidly. Identifying and clearing a particular frequency band involves high costs and long timescales. Thus, spectrum sharing is seen as a potential solution to make available underutilised frequencies which may already be assigned to other users while ensuring existing users retain access to the spectrum they need.

Two traditional approaches to sharing – **classical sharing** and **commons** – are well understood. The classical approach involves the granting of licences to a few selected users (e.g. a satellite operator and a fixed link operator) within the same frequency band. The users are subject to fixed and stringent operational rules, such as power limits and geographic exclusion zones, to mitigate any harmful interference. On the other hand, under the commons (licence-exempt) approach, all users can access if they use equipment that adheres to prescribed rules which might limit transmit power, duty cycle, bandwidth or other parameters.

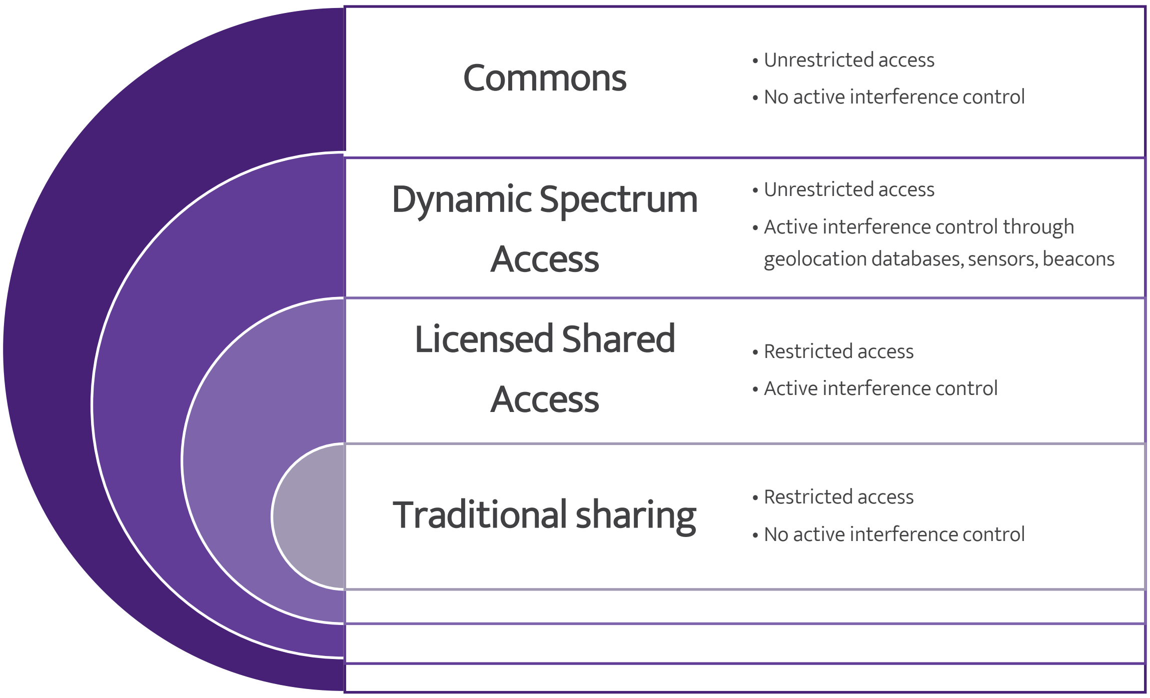
Recent developments around **Dynamic Spectrum Access** (DSA) and **Licensed Shared Access** (LSA) have provided more innovative possibilities for spectrum sharing. The shared use may be based on time, duration or geographic limitations and allow a higher degree of flexibility than classical sharing.

DSA typically involves the use of technologies such as geolocation databases, sensors and beacons, to determine if a particular frequency is in use at a specific location and whether transmitting at this frequency would result in interference to other users before access is granted. Examples of this approach include the use of TV white space in the UHF band and the proposed Citizen Broadband Radio Service (CBRS) in the 3.5 GHz band in the United States [6]

LSA is designed to allow a limited number of additional users into a band on a licensed basis. This might just be one other user in some cases. LSA is currently primarily foreseen as a mechanism to enable mobile broadband operators to access spectrum that has been harmonised in their region for mobile broadband use but where there are incumbents that are difficult to relocate. The idea is to award a block licence but with the requirement to share with the incumbent. This approach is particularly useful where the incumbent is a government user such as the military or aeronautical sector. Frequency bands under consideration for LSA in some countries include the 2.3 GHz band.[7]

Figure 2.2 provides a comparison of the key features of the different assignment methods.

Figure 2.2: Types of sharing approaches



[6] Plum Consulting. Flexible Spectrum Access Methods. Report for the UK Spectrum Policy Forum. 17 October 2017.
[7] Pilots and trials have been conducted in a number of EU countries, but it is still unclear if there is sufficient interest for LSA to be adopted. https://cept.org/ecc/topics/lsa-implementation

2.4 Trading and leasing

Based on economic theory secondary markets have an important role in delivering optimal use of spectrum. Secondary market activity comprises trading and leasing of spectrum licences – the main distinction between spectrum trading and leasing relates to the ownership of the licence. Trading involves a transfer of a spectrum licence between two parties and would often require the approval of the regulator. Leasing, on the other hand, does not involve a licence transfer; instead the leaseholder gains access to spectrum through a commercially agreed lease contract with an existing licence-holder. Spectrum leasing does not necessarily require regulatory involvement although in some countries, the regulator needs to be notified of leases.

In theory secondary market activity facilitates more efficient use of scarce resources as it allows users to acquire the spectrum they need and sell off unused or underused spectrum to those who value the resource more highly. This has the effect of improving allocative efficiency. [8] Furthermore, trading and leasing provides opportunities for new market players to obtain spectrum and develop new business, thus promoting dynamic efficiency.

Spectrum trading and leasing are permitted in many countries around the world but there has been relatively little secondary market activity involving cellular mobile spectrum.[9] In Europe, while the Framework for Electronic Communications Networks and services, provides a baseline on spectrum trading,[10] implementation of these measures across the EU is not uniform and there are variations in both scope and procedure between Member States. Also, regulation tends to assume that trades and leases of mobile spectrum will be between public mobile operators on a dedicated national basis. Most regulators have not yet factored into their thinking that leases could be localised in nature.

The economics of providing radio services affects users' interest in buying, selling or leasing spectrum. Factors that potentially reduce demand for and supply of traded spectrum include:

- **Lack of complementarity between spectrum use and the underlying radio infrastructure**. In many cases spectrum cannot readily be released and used without changing equipment. The costs of making these changes can be significant relative to the value of the spectrum and so act as an impediment to frequent trading of spectrum.

- **Potential buyers of spectrum may choose to meet their communications requirements through purchasing network access rather than investing in infrastructure and spectrum.** Potential substitutes for spectrum access include access to public trunked land mobile systems, MVNO arrangements for cellular suppliers, and purchasing leased lines rather than self-supplying fixed links.

- **Access to unlicensed spectrum may be a low-cost substitute for a spectrum purchase.** The use of unlicensed bands may substitute for licensed spectrum for delivery of a range of possible

[8] See Martin Cave and William Webb (2015). Spectrum Management: using the airwaves for maximum social and economic benefit. Working Party on Telecommunication and Information Services Policies – Secondary markets for spectrum: Policy issues, OECD 2005

[9] Spectrum trades tend to be more common in markets with regional spectrum licences (e.g. the United States, India) rather than national licences, as there are more market players.

[10] Through the Framework and Authorisation Directives.

services including broadband[11] and machine-to-machine and Internet of Things (IoT) applications.

- **Harmonisation of spectrum bands for uses and associated equipment standardisation reduces the potential to move spectrum to a higher value use.** Only in very large markets are spectrum licensees able to offer equipment vendors the scale required to produce low cost equipment – in these cases large increases in spectrum value may be realised through trades.[12]
- **Market structure and strategic behaviour may reduce willingness to trade or lease spectrum**. Most mobile markets comprise just a handful of market players who often view spectrum as a strategic asset that enhances their competitive positions in the market.

2.5 Implications for private LTE

There are several implications for private LTE arising from the discussion of the various regulatory and spectrum management aspects above.

In terms of licence type, both apparatus and block licences could be suitable depending on the nature of use and the deployment model. For small area deployments with one or a few transmitters, apparatus licensing may suffice. On the other hand, a block licence covering a large geographic area would be preferable for operators of wholesale private LTE networks. Licence exempt spectrum could also be useful depending on the quality of service and reliability requirements.

In terms of assignment method, the main issue is whether there is excess demand for the frequencies identified for private LTE use. For existing LTE bands already assigned to mobile operators, it is almost certain that there would be excess demand, particularly if block licences with national coverage are used. In such cases, an auction would be the most appropriate award method. However, given the largely localised nature of private LTE use, an auction is likely to see a private LTE user being outbid by mobile operators.

Beauty contests are problematic due to the different use cases for public LTE and private LTE – assessing bids based on a same set of evaluation criteria (e.g. coverage, quality of service) may not make sense. Direct awards are likely to be controversial particularly if there are competing use cases and users.

There are several possible scenarios and regulatory solutions for access to spectrum for private LTE use:

- Use of regional or local block licences – this would give potential private LTE users a better chance of acquiring spectrum through an auction as they would only be bidding for small area licences which mobile operators may not necessarily value as highly as national licences.

[11] Through techniques such as LTE-LAA and MuLTEfire.

[12] An example is the 1452-1492 MHz band which had been allocated for digital audio broadcasting but largely unused across Europe. It has taken several years to achieve a change of use for mobile broadband through new harmonisation measures developed by CEPT. In the UK, Qualcomm which initially bought the spectrum for £8.3 million in 2008 traded it to Vodafone and Three in 2015 for between £100 million and £200 million.

- Allocate specific bands for private LTE – this would ensure dedicated spectrum access for private LTE use. Some form of sharing (e.g. classical, LSA, DSA) may be involved. Potential bands would be non-core cellular bands (e.g. 2.3 GHz TDD[13], 2.6 GHz TDD[14]) or new bands (e.g. 3.8 – 4.2 GHz, mmWave bands). These frequencies could either be assigned to private LTE use via auction, beauty contest or direct award as appropriate depending on licence type and level of demand. This approach could support direct deployments or a wholesale model.

- Trading and leasing – secondary markets are an avenue for private LTE users to acquire spectrum but past experience involving mobile spectrum trades suggests a number of challenges

  – Trading is complicated by the fact that public mobile and private LTE have very different use cases which makes the transfer of a public mobile licence with its corresponding licence conditions and obligations to a private LTE use highly impractical.

  – Leasing is a more realistic option, but the appropriate regulatory framework and financial incentives need to be present for this to happen. Flexibility for licence holders, mobile operators in most cases, to set the terms of the leasing agreement and transaction costs (e.g. approval processes, negotiations) need to be reduced as much as possible.

  – There may be reluctance on the part of existing mobile operators to lease spectrum as they may view private LTE as a potential threat or may have plans to offer these services themselves. Regulators could consider 'use it or lose it' requirements to prevent hoarding and encourage leasing but the effectiveness and enforceability of such measures have been questioned.[15]

[13] 3GPP Band 33 (1900-1920) and Band 34 (2010-2025).

[14] 3GPP Band 38 (2570-2620 MHz). For example, in France ARCEP is planning to use the 2.6 GHz TDD band to upgrade PMR systems to superfast systems. See [link]

[15] Ofcom has argued that 'use it or lose it' provisions are unlikely to be effective at encouraging efficient use of spectrum as such conditions can be extremely difficult to monitor, not least due to the problem of identifying whether or not spectrum is actually being hoarded or used inefficiently. See Ofcom statement. Ensuring effective competition following the introduction of spectrum trading. 29 September 2004. https://www.nkom.no/marked/markedsregulering-smp/anbefaling-2016/marked-4

3 Ways of valuing spectrum

In general, the value of an input is the benefit that can be derived from that input. Spectrum can be used in many ways by different users and with many different outcomes. A new entrant may use spectrum to form its initial coverage network in suburban areas; an established operator may use the same spectrum to increase capacity in rural areas for high-speed mobile broadband; a broadcaster may wish to use the same spectrum to expand its number of channels; a private LTE operator may use the spectrum to provide a small area local network to support specific enterprise applications such as industrial automation. Each of these users will value the spectrum differently.

The value of spectrum is a result of the benefits that could be generated from the use of the spectrum. For mobile bands, this relates to two main aspects:

- The use of spectrum to **reduce cost** – the spectrum is used instead of physical network components such as new base stations to support traffic growth on an existing service, or instead of fibre links to allow for data transmission. The value here is the reduction in cost, namely, cost savings obtained from using the spectrum

- The use of spectrum to **generate extra revenue** – either through a new service or otherwise to help the company compete effectively in the market and protect its market share and future revenue stream. The value here will therefore relate to the stream of future cash flow for the company.

There is a third aspect, namely option value[16], which may be relevant in cases where a spectrum licence is tradeable, renewable or fungible in terms of a change in use. These characteristics confer advantages that may influence a firm's willingness to pay for spectrum.

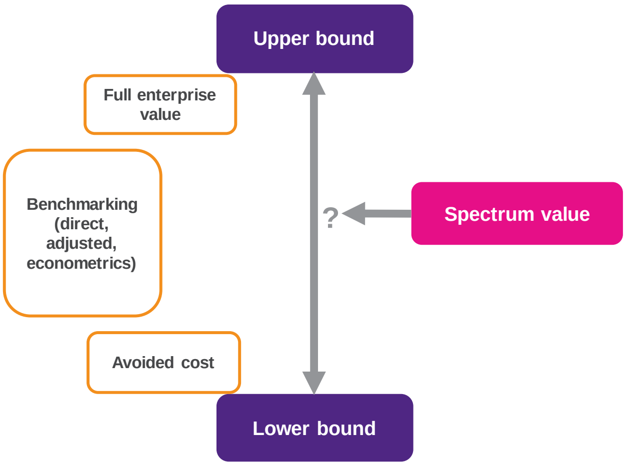
In cases where spectrum is auctioned, its value is revealed in the market clearing prices. Prices paid in an efficient spectrum auction will reflect the value of an incremental spectrum lot to the marginal bidder – either the lowest value for a winning bidder or highest value for a losing bidder. Rational bidders should not pay more than the net present value of future cash flows from use of the spectrum – this is commonly referred to as the **full enterprise value** and represents the upper bound on value. However rational bidders should be willing to pay more than the infrastructure costs saved from having an incremental lot of spectrum – this is called the **cost reduction value** or the **avoided cost value** and represents the lower bound on value. The market price would lie somewhere between the full enterprise value and the cost reduction value.

Market benchmarks provide indications on actual amounts paid elsewhere and these in theory will fall between the full enterprise value and cost reduction value. In some cases, however, benchmarks could also lie outside this range, depending on whether the specific circumstances of the award and the

[16] The option value of spectrum is the value to a firm of having the flexibility to invest at the optimal time; where there are irreversible costs associated with making investments, there is the possibility of waiting for new information to arrive and potentially avoiding or reducing uncertainty over investment returns. See "Aegis and Plum (2009). Estimating the commercial trading value of spectrum. A report for Ofcom."

bidding behaviour and strategy of participants. Figure 3.1 illustrates the different aspects of spectrum value.

Figure 3.1: Ranges on spectrum value



Valuation methodologies can be classified into two general categories – benchmarking and modelling. Under each category there are several different approaches as shown in Figure 3.2. Appendix A describes each methodology and assesses their advantages and disadvantages.

Figure 3.2: Valuation methodologies for mobile spectrum

Benchmarking approaches	Modelling approaches
• Direct benchmarking • Adjusted benchmarking • Econometrics	• Avoided cost models • Full enterprise valuation • Iterated cost models

Figure 3.3 summarises the advantages and disadvantages of the different valuation methodologies. Each methodology has its strengths and weaknesses and stakeholders usually adopt a combination of methodologies to estimate the value of spectrum.

Figure 3.3: Advantages and disadvantages of various valuation methodologies

Valuation methodology	Advantages	Disadvantages
Direct benchmarking	Simple and easy to understand Reflects actual prices paid by operators for similar spectrum bands Transparent as it is based on published auction results and not assumptions and detailed modelling	Large dataset needed There may be a lack of data points for certain bands May be difficult to make 'like for like' comparisons as international benchmarks may reflect country and operator-specific circumstances

Valuation methodology	Advantages	Disadvantages
Adjusted benchmarking	Transparent as it is based on published auction results Can be used when have relatively few data points	Ratios for other countries may reflect auction or business-specific factors which may not be comparable to the local context There may be a lack of data points for certain bands
Econometrics	Robust statistical method if suitable data exists Possible to assess the effects of different drivers of spectrum value Relies on actual prices paid	Large dataset needed Quantitative information on certain drivers of value may not be available and thus cannot be captured in the analysis Regression models may not provide stable forecast of spectrum value, especially where sample size is limited
Avoided cost modelling	Country-specific context and operator-specific information can be directly captured in the model Provides outputs on infrastructure requirements (such as base stations) which is not possible with benchmarking methods	Complex modelling required Requires access to information which may not be available, though some international benchmarks may be used to supplement local data Results may be highly sensitive to input and network assumptions Less practical as a way of deriving value for a new entrant
Full enterprise value or business modelling	Theoretically this provides an upper bound on spectrum value to an operator as it estimates profits from running a mobile network; this gives an indication of an upper limit on what regulators and governments can charge for spectrum	Results likely to overestimate the value of spectrum Complex modelling requiring accurate forecasts of future costs and revenues which may not be available Considerable uncertainty in results given information asymmetry between regulator and operators, and substantial differences in business cases among operators and potential new entrants

As there is no one correct or best approach to spectrum valuation, most regulators and industry players tend to prefer to apply more than one methodology to improve confidence in the valuation results. Figure 3.4 provides an overview of the methods used in different countries for valuing public mobile spectrum.

Figure 3.4: Methodologies used for valuation of mobile spectrum

Country, year, institution, purpose	Band (MHz)	Benchmarking		Modelling	
		Direct/ adjusted	**Econometrics**	**Avoided cost**	**Enterprise values**
New Zealand. Ministry of Economic Development 2007 (licence renewal)	850, 900	✓	✓	✓	×
Australia. DBCDE 2012 (licence renewal)	850, 1800, 2100	✓	×	✓	✓
Ireland. ComReg 2012 (reserve price)	800, 900, 1800	✓	✓	×	×
India. TRAI 2013 (reserve price)	850, 900, 1800	×	✓	✓	×
Hong Kong. CA & CEDB 2013 (licence renewal & reserve prices)	2100	✓	×	×	×
India. TRAI 2014 (reserve price)	2100	✓	×	✓	✓
Thailand. NBTC 2015 (reserve price)	900, 1800	✓	✓	✓	✓
UK. Ofcom 2013 (reserve price)	800, 2500	✓	×	✓	✓
UK. Ofcom 2015 (licence fee revision)	900, 1800	✓	×	×	×

3.1 Application to private LTE

As the frequencies for private LTE would be also usable for public mobile in most cases, we will need to consider how the methodologies are applied from the perspectives of the two different use cases. There are a number of issues when applying the above valuation methods to private LTE.

- Benchmarking – there is a lack of benchmarks for private LTE (Professional Mobile Radio - PMR - values might be useful but there are very few market benchmarks and frequencies are different); public mobile benchmarks which tend to be based on licences covering large geographic areas may not be an accurate indication of private LTE value given the different use case and business models. While some adjustments and normalisation can be made, public mobile benchmarks would still be expected to give higher values that may not be representative of private LTE.

- Business modelling may not be appropriate as spectrum is not a direct input to the services provided by the private LTE user (except in the case of a wholesale operator). There would usually be substitutes to the use of private LTE (e.g. fixed networks, other radio technologies). There are a variety of use cases and information requirements, and assumptions needed to carry out the modelling are likely to be significant and these may affect the reliability of the results.

- Avoided cost modelling approach is likely to be more appropriate to estimate the opportunity cost of spectrum. This can be done from two different perspectives – public mobile and private LTE.
  - From the public mobile perspective, the geographic location or coverage of the private LTE network is needed to work out the "deprival value" for the public mobile user.
  - For private LTE, information on the alternative solutions for the private LTE user is needed to work out spectrum value based on the least cost alternative. This will involve an assessment of the viable alternatives (e.g. using other bands, fixed links, leased lines, etc.) to achieve the same output and the costs involved in implementing these.

Figure 3.5 provides an overview of the issues when applying the different valuation methods to value private LTE spectrum from the public mobile and private LTE perspectives.

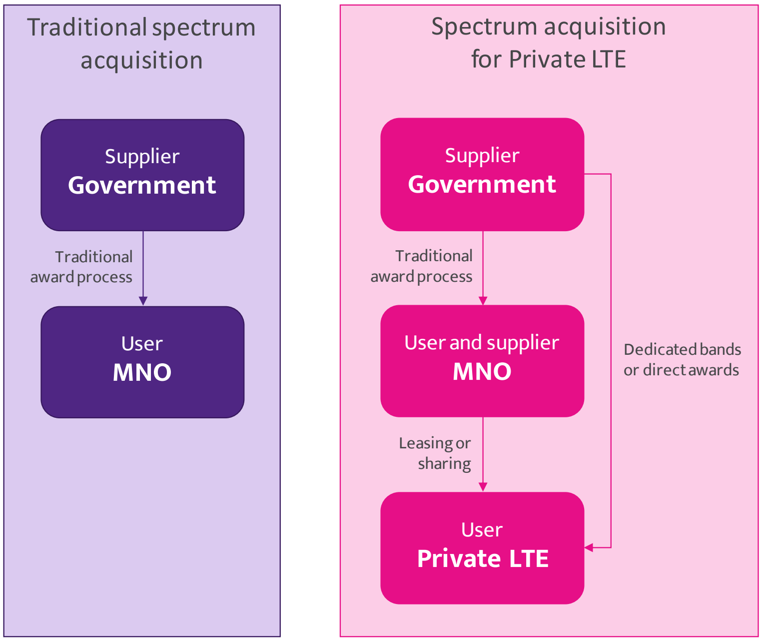
Figure 3.5: Valuation methods and their applicability to private LTE spectrum

Valuation method	Public mobile	Private LTE
Benchmarking	Lots of auction benchmark values but may not be representative of private LTE value. Some adjustments can be made but may be unreliable.	Very few auction benchmarks; some PMR auctions but tend to be in lower frequency bands (400 MHz).
Avoided cost modelling (least cost alternative)	Avoided cost modelling can be undertaken to estimate public mobile opportunity cost for spectrum but needs geographic-specific information on private LTE deployment and demand for public mobile. Results will be sensitive to assumptions.	Can be done from private LTE perspective by considering least cost alternatives (e.g. other bands, fixed links, leased lines, etc.). Potentially a lot of information required, and this will differ by use case.
Business modelling	Complicated and may not be feasible to do this on a non-national basis. Results will be sensitive to assumptions and significant risk of overestimation.	Business model for private LTE uncertain. May not be possible if spectrum is not a direct input to output.

4 The valuation of spectrum used for private LTE

As discussed above in Sections 2 and 3, the private LTE market will operate in a different way from that of other users of spectrum, and as a result the usual methods of assigning and valuing spectrum are not possible. In particular, traditional spectrum awards took place between the government (supplying) and the operators (demanding). However, when spectrum is shared, as is required for private LTE, the operators become the suppliers and there are new entrant demanders.

Figure 4.1: Comparison of spectrum acquisition



Not only are the holders of spectrum different entities, but the way in which spectrum is used is significantly different as well. Note that in the case of spectrum acquisition for private LTE, the middle box (User and supplier) could be a wholesaler rather than an MNO.

4.1 The disadvantages of normal market mechanisms

Therefore, when considering the best way to award and value spectrum when used for private LTE, we need to take account of how both supply and demand differ. This will then inform why the standard market mechanisms will not work, and how spectrum assignment should be approached.

4.1.1 Differences in the supply of spectrum

When looking at the supply of spectrum, the key differences are caused by who the supplier is. In traditional spectrum awards, the single supplier is the government or the regulator, who owns the right to award the entirety of the spectrum. The government's incentives are generally to maximise economic and social benefit through the award of spectrum, and to do this it carefully controls the allocation and assignment of bands. Although this assignment is managed, there are large amounts of spectrum to be allocated between potential uses.

On the other hand, spectrum to be used by private LTE networks is currently owned by private companies, usually mobile operators, who have a single objective of profit maximisation (although they may also consider ensuring they are not enabling competition). While the incentives are clearer, there are multiple potential suppliers of the spectrum, making valuation a more difficult exercise.

There are further differences in the spectrum itself. Spectrum awarded by government is usually backed up with guaranteed interference parameters, and the owners of this spectrum have primary use of it. Spectrum leased to private LTE networks, on the other hand, will be much more restricted, and may itself be bound to not interfere with the MNO's own use.

Finally, there is currently no obligation for operators to share spectrum, while the government sets targets over how much spectrum is to be released on a more traditional basis.

4.1.2 Differences in the demand for spectrum

The way that potential licensees use spectrum is a further difference. Private LTE networks are, by their very nature, designed to be small-scale, sub-national and sometimes short-term. Spectrum requirements are often agile and temporary. As a result, any licences that are only available on a national basis, with long licence durations, are not suitable, and will be unaffordable by private LTE operators.

A further difference is the reliance on spectrum. Mobile network operators need appropriate spectrum to underpin their business, and so it is a crucial input. The extent to which the users of private LTE will rely on these networks will vary by use, but in most cases, there will be an alternative technology that can be used to communicate and share data. Certainly, the provision of a mobile network is not the key objective for these users; it is simply an input to other output. The alternative technology here may, for example, be a legacy wireless technology, or a fixed network with unlicensed wireless ends, but alternative technologies will each have their own non-financial advantages and disadvantages that will need to be taken into account – for example, use of unlicensed spectrum potentially reduces quality of service.

This fact also will restrict the value that potential licensees can place on spectrum. If spectrum prices as a whole increase, then mobile operators can increase data or call prices to reflect this. However, private LTE networks cannot increase the revenue associated with their use, since these prices will be determined in an entirely different competitive market.

Demand for spectrum – and the value placed on this spectrum – will therefore vary depending on the way that private LTE networks will be used. This will make analysis of the market for either side difficult, and this uncertainty will lead to delays in any licencing agreements. Certainly, there may be expectations from mobile operators that the value of spectrum to other users will be higher than it actually is – many of the potential uses of private LTE networks have low values, and after the purchase of network equipment there may be little scope for expensive spectrum leasing.

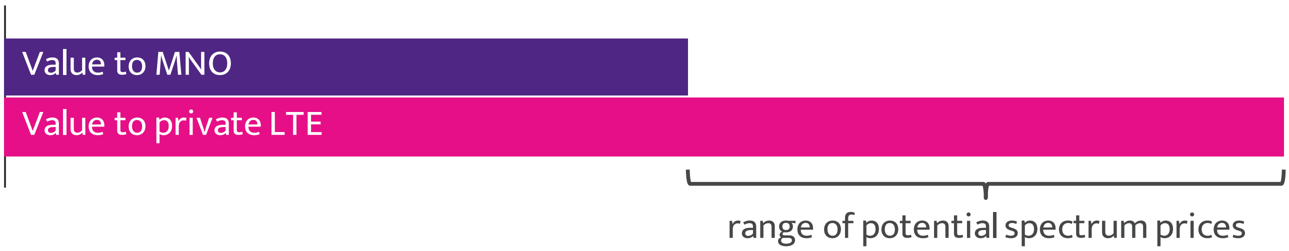
4.1.3 Setting an appropriate price

Following from above, for spectrum sharing to take place, there are two conditions that must be met:

- The supplier – the MNO – must be incentivised to share spectrum
- The demander – the private LTE network operator – must obtain a high enough value from using the spectrum.

These conditions both involve financial valuations; for spectrum to be shared, the price paid must be higher than the value the MNO would otherwise obtain but must be lower than the value the private LTE operator will realise.

Figure 4.2: Setting spectrum sharing prices



The uncertainty comes from asymmetric information. Given the above, there is an upper bound on the total price that may be paid for spectrum, being the value that private LTE network operators will realise from it, but mobile network operators will be unaware of this. Similarly, private LTE operators will have no definite knowledge of the value of the spectrum to the MNO.

4.2 Use of opportunity cost valuation

As the value that the private LTE network operator will realise is so uncertain, it is not possible for MNOs to set prices for spectrum at a profit-maximising level. Instead, it is useful to consider the minimum price that may result in spectrum sharing. This minimum price will be at a level which incentivises the MNOs to share their spectrum and is dependent on the conditions of sharing itself.

As the MNOs' main objective is to maximise profit, they will be incentivised to share spectrum if the revenue they obtain from this spectrum is greater than the cost of enabling sharing. Generally, there will be little direct cost in sharing spectrum, but instead they may suffer an opportunity cost which arises from them no longer having access to the spectrum.

This opportunity cost will vary depending on how the private LTE network is to be operated. If the networks are designed for highly rural locations, where the MNO has no plans to expand their coverage, then there is a very low opportunity cost. Indeed, where only part of the total spectrum holding is used, particularly spectrum in the 2600 MHz band or higher, then the MNO will likely suffer no opportunity cost – if they did, in the future, wish to expand their networks to cover these areas, they would likely do so using sub-2 GHz spectrum.

Even in more urban locations, opportunity cost may be small if the private LTE use is for a limited timeframe, during which the MNO has no plan for network expansion; if there is a possibility of future need for the spectrum, then the MNO could build a break clause into the sharing contract to enable them to take back what is needed. If it is only in dense urban locations, where the MNO is already using the spectrum or has plans to imminently do so, that opportunity cost may be significantly higher.

MNOs are uniquely placed to carry out this opportunity cost valuation, as it relies on running scenarios on their business plans and network rollout plans. Provided that a MNO's plans are sufficiently detailed in the geographic area the private LTE network is intended to cover, there should be little difficulty in understanding how sharing spectrum would affect (or not affect) the MNO's business plan. The opportunity cost will be calculated as the sum of:

- Additional equipment costs incurred due to not having access to spectrum, and
- Any revenues foregone due to spectrum being unavailable.

Given the likely low opportunity costs, as long as direct costs are covered (and there is a small additional payment to encourage sharing) there is no rational reason for MNOs to refuse to share. The direct costs may cover consultancy over licences, monitoring and interference analysis, legal advice and negotiation time; although these costs may be high when sharing is first carried out, there are large economies of scale which will bring down the cost per deal in future years.

4.3 Use of other valuation methods

While the opportunity cost valuation provides a rational MNO with a minimum price that they should accept for sharing spectrum (and any price above this minimum should be accepted), as a profit maximising entity there will be a desire to extract the maximum possible revenue from the private LTE operator.

There are two methods the MNO might try to use to do this:

- Using their own business models to estimate the value of spectrum; or
- Carrying out bespoke business analysis and valuation.

To do the second of these, the MNO would wish to estimate the value that the potential licensee could realise. Section 3.1 of this report has already considered how traditional valuation methodologies will not be sufficient to do this. Because each private LTE business case is distinct, carrying out a bespoke business model will be an unrealistic exercise, as the cost of such an exercise would be disproportionate to the likely revenue. Similarly, there is unlikely to be an available benchmark value. If MNOs looked to perform their own valuations on spectrum use, it is likely that the overall cost of licencing would exceed the likely benefits that could be obtained (on either side of the market).

It is therefore possible that MNOs will attempt to use their own business models and network plans to estimate a value of spectrum for private LTE. Even if appropriate adjustments are made for geographic reach or licence duration, this will overestimate the value to private LTE networks:

- Private LTE networks are an input to another industry and are not crucial to the operating of that industry. The value of the private LTE network is only the cost saved by not using an alternative, rather than the total profit that can be extracted. Note that the value of spectrum used by alternative technologies is not an appropriate way of valuing spectrum used by private LTE, since all other costs will vary considerably.

- If the value of operating private LTE was equal to or greater than the value of the public network, then the potential private network operator would be willing to fund network expansion by the MNO and benefit from economies of scale.

Since benefits of private LTE are comparatively small, if MNOs attempt to maximise profit using these methods, the likelihood is that they will price potential sharers out of the market.

4.4 Issues arising from low valuation

This low value of spectrum – on both sides of the market – may cause issues itself. Even if MNOs seek to charge the opportunity cost alone, and private LTE operators value the spectrum higher than this, there may be administrative difficulties to overcome which will prevent the private LTE networks from being commissioned. As will be discussed in Section 5, any significant regulatory burden is likely to prevent use. In addition, if MNOs impose strict obligations or restrictions on spectrum use, then it is possible that potential licensees will find their business cases untenable.

Therefore, to facilitate the use of spectrum for private LTE, the administrative burden must be reduced as much as possible. This applies both to MNOs, who should formulate standard procedures for spectrum sharing and leasing, and to regulators who should ensure that:

- MNO licenses allow for sharing with no disadvantages; and

- The registration or licencing procedure for private LTE networks is very light-touch.

If the licencing regime is overly onerous, this may prevent dynamic and small-scale trading, which will be required by a number of private LTE use-cases.

4.5 Alternative market structures

This report has, thus far, considered a market where there is a supplier of spectrum (typically an MNO) and a licensee (the private LTE network operator). However, it is possible that alternative market structures may work better for all parties. Below, reserved spectrum for private LTE, wholesale provision and brokerage are discussed. In the case of the latter two approaches it should be noted that they provide the possibility to:

- Simplify the arrangements required between enterprises and mobile network operators; and
- Reduce administrative complexity and costs.

4.5.1 Reserved spectrum for private LTE

The most obvious alternative source of spectrum for private LTE networks is the government or regulator. In many spectrum awards around the world, there is nothing to prevent new entrants buying spectrum in higher frequencies – lower frequencies (in particular, sub-1 GHz) often carry a coverage obligation which would be impossible for private LTE networks to meet. However, the levels of competition in auctions and the high reserve prices placed on lots – along with the national licencing regime and long licence durations – mean that is infeasible for private LTE operators to win spectrum in this way.

Instead, regulators may choose to set aside a certain amount of spectrum for private LTE use. This would not be an efficient regulatory measure, as it would not allow spectrum to be used to the fullest extent possible. In addition, it would require the government to manage multiple small-scale licences and specify detailed rules to prevent the MNOs from buying multiple local licences to extend their national coverage.

4.5.2 Wholesale spectrum provision

Rather than government reserving spectrum which could then be licensed to multiple private LTE networks, it may instead set aside a certain lot to be used by a wholesale spectrum provider(s). This provider would be awarded, say, 2×20 MHz of 2600 MHz spectrum, and would then be able to lease this to MNOs, private LTE operators, or other users, on a sub-national, short-term basis. The government may see this as a preferable option, as it would mean that it would no longer have to deal with micro licensing spectrum to all potential users.

While it may be possible for an independent company to buy spectrum in an auction and carry out this role, the high prices of spectrum contrasting with the low value of private LTE networks would make this an unlikely business case. Instead, the wholesaler would rely on MNOs needing extra capacity in urban areas and would use the fees paid by those operators to effectively subsidise private LTE. In general, there are few restrictions to the deployment of wholesale networks, although in addition to spectrum licenses, there is usually a requirement for an authorisation or licence to operate a private network.

4.5.3 Brokerage

Much of the market inefficiency described in this Section arises from uncertainty of information asymmetry. Rather than having a single buyer and seller market, it may be more efficient to introduce a third party to arrange spectrum trading. Such a broker would be able to aggregate private LTE use, discuss demand with all MNOs in the market, and find the optimum sharing mechanism.

Brokerage would have several advantages.

- Administrative burden – in terms of contract drafting, setting obligations, price negotiations – would be simplified and benefit from large economies of scale.
- Valuations for spectrum would likely be more realistic, since the broker would be able to understand potential private LTE business cases and would not have unrealistic expectations over the value of mobile spectrum.
- Potential licensees would be able to approach a single contact rather than have to compare spectrum offerings from multiple MNOs.
- Brokers could add certainty to private LTE networks while allowing MNOs the flexibility to withdraw their spectrum from sharing if needed.

5 Benchmarking analysis

This section presents a short direct benchmarking analysis of selected frequency bands. In particular we examine past values for non-mainstream bands such as the 2600 MHz TDD and the 3400 – 3800 MHz which have not yet been widely deployed for public mobile services and thus may be considered more appropriate indicators of value for private LTE.

The dataset for the direct benchmarking includes observations from 2015 onwards for the 3400-3800 MHz sample[17] and from 2010 for the 2600 MHz TDD sample. The benchmarking sample comprises of values from auctions[18] as these are the most representative of market value. The auction results are converted from local currency to USD. The benchmark values are presented in real USD[19] and adjusted to a licence duration of 15-years and normalised by bandwidth of award and population (per MHz pop).

5.1 3400 – 3800 MHz

The 3400 – 3800 MHz results include 14 observations; these are shown below in Figure 5.1 and Figure 5.2.

Figure 5.1: 3400 – 3800 MHz auction results (USD real)

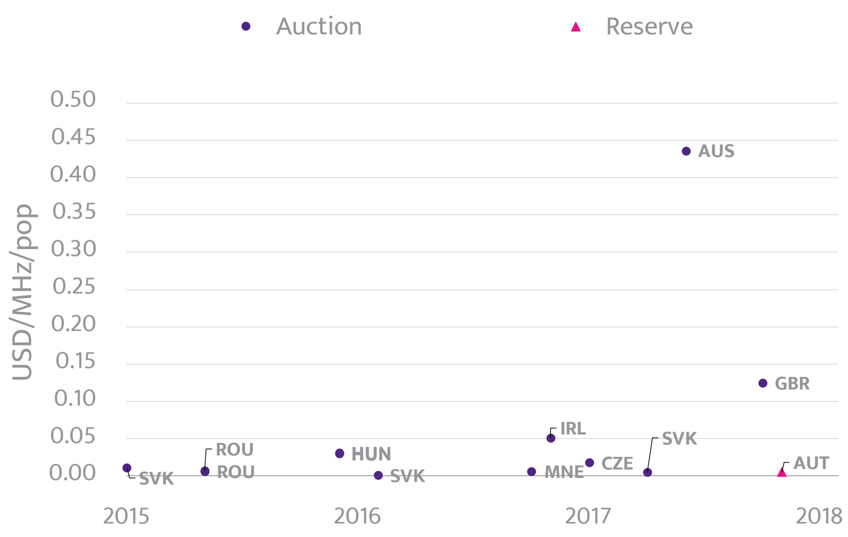


Figure 5.2: 3400 – 3800 MHz auction results (adjusted for 15-year duration, real 2018)

Country	Frequencies offered	Auction date	Bandwidth sold (MHz)	USD/MHz/pop
Slovakia	3.6 – 3.8 GHz	02/2015	120	0.0026

[17] Data from earlier auctions (e.g. WiMax) is unlikely to be applicable due to differences in technology and rollout models.
[18] Direct awards, annual licence fees and trade values are excluded from our sample.
[19] Revised for inflation to be equivalent to 2018 auction determined price.

Country	Frequencies offered	Auction date	Bandwidth sold (MHz)	USD/MHz/pop
Slovakia	3.4 – 3.6 GHz	07/2015	60	0.0104
Romania	3.4 – 3.6 GHz, FDD	11/2015	110	0.0062
Romania	3.6 – 3.8 GHz, TDD	11/2015	145	0.0060
Hungary	3.4 – 3.6 GHz, FDD	06/2016	60	0.0299
Hungary	3.6 – 3.8 GHz, TDD	06/2016	20	0.0286
Slovakia (1)	3.4 – 3.6 GHz	08/2016	80	0.0004 (sample min.)
Montenegro(1)	3.4 -3.8 GHz	04/2017	50	0.0057
Ireland (1)	3.4 – 3.8 GHz	05/2017	350	0.0499
Czech Republic	3.4 – 3.6 GHz	07/2017	200	0.0171
Slovakia (1)	3.4 – 3.6 GHz	10/2017	120	0.0042
Australia (1)	3.4 – 3.6 GHz	12/2017	7	0.4249 (sample max.)
United Kingdom	3.4 – 3.6 GHz	03/2018	150	0.1261
Austria	3.4 – 3.8 GHz	03/2018	390	0.0049 (2)
Mean sample value (excluding reserve price)				0.05

Note: (1) Frequencies offered as regional licences; (2) reserve price.

Although the benchmark sample is relatively small (n=14), we can identify wide variation in the results with the average USD/MHz/pop ranging from 0.0004 to 0.4249. Two observations (Australia 2017, UK 2018) have an auction determined price above the mean of 0.05 USD/MHz/pop.

The regional awards (Slovakia, Montenegro) offers some of the lowest auction values – if excluding the Australian award. However, as there are only a few observations for regional licences, it is difficult to determine through a simple benchmarking exercise whether the lower auction price is due to the regional coverage of the licences or other factors such as low demand or market-specific characteristics.

However, in stark comparison, the Australian (2017) auction – which was a residual auction offering spectrum in metropolitan areas[20] – achieved a substantially higher result compared to the rest of the sample. There was high variation in the price achieved in the eight licences sold (one licence offering 2600 MHz in Canberra was unsold); ranges of 0.004[21] to 1.26[22] USD/MHz/pop. The winning prices (unadjusted for bandwidth and population) varied from USD 2,348 [23] to USD 39,134,500[24]. The licences were predominantly bought by MNOs Optus and Telstra, and NBN Co (a government-owned corporation tasked with increasing fixed and mobile broadband access). A possible explanation in the

[20] The 3.4 GHz spectrum offered regional licences in the following areas: Adelaide, Brisbane, Canberra, Hobart, Launceston, Rockhampton, Sydney, and Toowoomba.
[21] Sydney licence offering 3.5 MHz sold for 0.0049 USD/MHz/pop.
[22] Hobart licence offering 3.5 MHz sold for 1.6089 USD/MHz/pop.
[23] Rockhampton licence offering 3.5 MHz. Population 120,890.
[24] Brisbane licence offering 32.5 MHz. Population 3,3093,768.

high auction value achieved in this auction is the growing interest in 3.4 – 3.8 GHz frequencies for 5G (for both mobile broadband and fixed wireless access services).

The 3.4 -3.8 GHz auction in Ireland (2017) offered 350 MHz bandwidth in nine regions (four rural and five urban) on 15-year licences[25]. The auction raised a total USD 96.5 million at auction (or 0.0499 USD/MHz/pop). No spectrum was reserved for new entrants but the bidders in the main stage of the auction were subject to a cap of 150 MHz in each region. All available lots were sold to five bidders – three established MNOs (Meteor, Three, Vodafone) and two new entrants (Imagine and Airspan). All three MNOs all bought spectrum in rural and metropolitan regions; paying between USD 19 million and USD 28 million.[26] Airspan, a vendor providing small cells solutions and a provider of 4G wireless broadband, bought 25 MHz spectrum in the rural regions and 60 MHz in metropolitan regions for a total payment of USD 11.2 million. Imagine, a fixed wireless broadband operator, won spectrum only in rural regions, paying USD 12.1 million for 60 MHz in the four rural regions.

In the 3.4 GHz UK auction, the four incumbent operators (EE, H3G, Telefonica and Vodafone) paid around USD 1.6 billion for the 150 MHz on offer.[27] Airspan which also participated in the auction failed to win any lots.

5.2 2600 MHz TDD

The 2600 MHz TDD sample comprises of 26 observations, all of which are auction results. The results are presented in Figure 5.3 and Figure 5.4.

[25] Bandwidth of lots offered varies – a 25 MHz lot was offered in 3410 – 3435 MHz, 5 lots if 65 MHz each were offered in 3475 – 3800 MHz. Populations for the regions ranged between 10–27% of national population in rural regions, 1-4% in most metropolitan regions and 24% in the metropolitan region of Dublin (CSO city and suburb); reserve prices and on-going annual licence fees for the regions were adjusted to account for population.

[26] Meteor Mobile bought 80 MHz in rural regions and 85 MHz in metropolitan regions for a total of 19.3 USD million. Three Ireland bought 100 MHz in each of the regional (equivalent to a national licence) for 25.2 USD million. Vodafone bought 85 MHz in rural regions and 105 MHz in metropolitan regions for 28 USD million.

[27] https://www.ofcom.org.uk/__data/assets/pdf_file/0018/112932/Regulation-111-Final-outcome-of-award.pdf

Figure 5.3: 2600 MHz TDD auction results

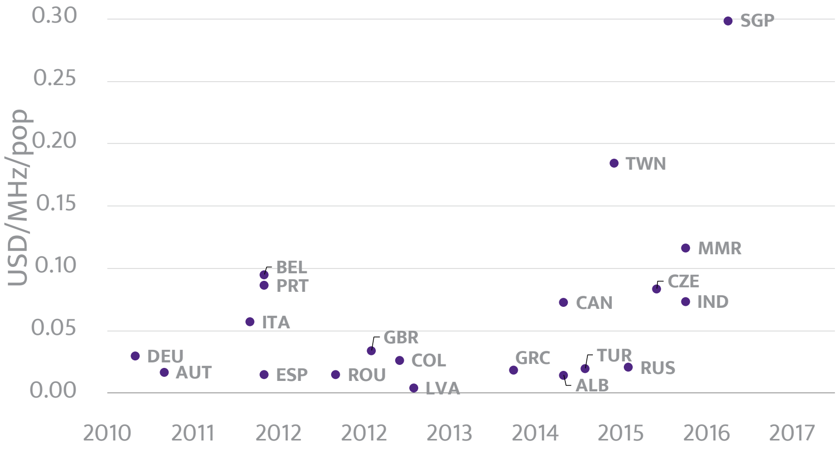


Figure 5.4: 2600 MHz TDD auction results (adjusted for 15-year duration, real 2018)

Country	Auction date	Bandwidth (MHz)	USD/MHz/pop
Germany	05/2010	50	0.0298
Austria	09/2010	50	0.0169
Italy	09/2011	30	0.0571
Portugal	11/2011	25	0.0862
Spain	11/2011	30	0.0149
Belgium	11/2011	45	0.0951
Romania	09/2012	45	0.0148
UK	02/2013	50	0.0340
Colombia	06/2013	40	0.0264
Latvia	08/2013	50	0.0039
Greece	10/2014	40	0.0184
Canada*	05/2015	25	0.0727
Albania	05/2015	20	0.0144 (sample min.)
Turkey	08/2015	35	0.0198
Taiwan	12/2015	50	0.1843
Russia*	02/2016	50	0.0207
Czech Republic	06/2016	50	0.0838
India*	10/2016	189	0.0733

Country	Auction date	Bandwidth (MHz)	USD/MHz/pop
Myanmar*	10/2016	40	0.1163
Singapore	04/2017	45	0.2986 (sample max.)
Mean sample value			0.0641

Note: * Frequencies offered as regional licences; bandwidth indicates average MHz sold.

The sample mean of 0.06 USD/MHz/pop appears to be relatively high in comparison to the range of values. The majority of observations are below 0.10 USD/MHz/pop and over half of observations are below 0.05 USD/MHz/pop. However, slightly higher values have been observed recently, for example, Singapore (2017) and Taiwan (2016). These higher auction prices skew the sample mean upwards.

5.3 Fee structure

The above benchmark analysis is not intended to provide a definitive answer on the value of private LTE spectrum; these values reported are more reflective of the market value for public mobile use. More detailed valuation analysis would be needed as discussed in Sections 3 and 4.

However, once the spectrum price has been determined either via auction or administratively, the next question is how this is to be paid. There are three types of payment mechanism to be considered:

- A lump sum, where the total price is paid at the start of the licence period;
- An annual fee, where the price is spread across the licence period (using a net present value calculation); and
- A hybrid approach, with part of the price being paid up-front and the rest being paid on an annual basis.

There is no one ideal approach here though there are some key principles that should be followed.[28]

- Transparency over the level of any fees that will be charged over the licence period: bidders need to know what proportion of fees will be required to be paid up front and the extent of any annual fees;
- Certainty that fees will be paid (and a clear understanding of what will happen if they are not): this is particularly important where all or part of the auction fees, are proportioned over the duration of the license; and
- Appropriate mechanisms in place to incentivise efficient use of the spectrum whilst avoiding undue burdens: this can be achieved through auction fees paid up front, annual licence fees or a combination of both.

[28] Radio Spectrum Policy Group. RSPG Report on Efficient Awards and Efficient Use of Spectrum. 24 February 2016.

5.3.1 Advantages and disadvantages

On-going annual fees could also boost demand for spectrum by reducing the need for an upfront payment, especially if they are well specified in advance of the auction. For example:

- Being able to defer part of the payment for licences may be valuable to bidders with a limited upfront budget, as reducing upfront payment needs may strengthen their position relative to competitors with a higher upfront budget (but who could possibly place a lower overall value on some of the lots offered); and

- In addition, on-going fees may lower the financial exposure for bidders who are uncertain about the value of lots: bidders could avoid the burden of any remaining on-going payments by returning the spectrum they acquired at a later date if it fails to achieve the value they expected.

These two points may be of particular importance in relation to private LTE, where availability of finance may vary significantly between users. If lump-sum payments were required, there is a possibility that small to medium enterprises would struggle to raise funds or they may be faced with a large financing cost, hence deterring them from implementing such solutions.

Depending on policy objectives, annual fees may be less attractive for regulators, who will be faced with some higher risk of non-payment if operators should become insolvent. This will also not satisfy a regulator which has been asked to raise funds for the national treasury through spectrum awards. On the other hand, where there is a clear policy objective to promote industry development and innovation, annual fees may be more appropriate especially in the context of new use cases related to private LTE and 5G.

6 Policy and regulation

A key enabler for private LTE is access to suitable harmonised spectrum. As already described there are several ways this could happen including use of spectrum leasing and sharing, or in the case of future spectrum awards through set aside or other mechanisms aimed at entry of non-mainstream operators. For leasing and sharing to be a practical way forward, there needs to be clarity on the operation of these mechanisms and a level of consistency between jurisdictions, if scale of private LTE is to be achieved. Also, a proportionate regulatory approach is required that will provide regulatory certainty for private LTE operators while minimising the burden and cost of regulation to both private LTE operators and regulators.

6.1 Status

To date there has been little leasing and sharing of spectrum (outside of the well-established static sharing in frequencies such as C-Band where satellite and fixed links share, and activities like PMSE). Leasing and sharing in harmonised mobile bands is virtually non-existent. While new concepts have been discussed for sharing, these are not mainstream activities for regulators and there is still an absence of clear incentives for these things to be pursued.

- A possible exception could be CBRS in the Unites States. CBRS is aimed at expanding spectrum supply for wireless broadband in the 3.5 GHz band in the light of perceived future demand for such spectrum based on evolution of the LTE ecosystem. CBRS will provide both light leases and opportunistic access, which could be suitable for private LTE. However, the approach is still in development and it is unclear how it will work in practice.

- LSA in Europe was conceived with a similar purpose to expand the supply of spectrum in the 2.3 GHz band for mobile broadband. LSA is specified and it is a regulatory mechanism rather than a new licensing approach. Its strength for private LTE is that it is conceived with provision of specified quality of service for both incumbent and sharer – it was defined to allow mobile network operators to share with government use. However, in the context of private LTE, mobile network operators would be the incumbent and private LTE the sharer. Regulators, who would be responsible for issuing licenses to sharers (private LTE), would need to take this change of context into account. If private LTE grows and many sharing licenses are required, scale could become a problem for regulators. A lighter licensing approach may be preferable.

6.2 Leasing

The concept of spectrum transfer (trading/leasing) has been around for many years, although it is only in the past decade that many governments have taken measures to enable transfer and there are still places where transfer is not possible (e.g. Hong Kong). For mobile services, transfer is envisaged as taking place between mobile operators or possibly as a means of allowing a new entrant. Key points are:

- Trades and leases were expected to mirror the basis on which spectrum licenses were originally issued (there are sometimes ex-ante competition checks applied to ensure that certain parameters are not breached).
- In the case of spectrum leasing, the mobile network operator originally licensed would remain responsible for compliance with licence/authorisation conditions (e.g. on network coverage).

The above could pose problems for both private LTE operators seeking access to spectrum on a localised basis and the mobile network operators holding spectrum. For example, what happens to compliance with a coverage condition if spectrum is leased? Hence, there is a need to:

- Define rules for transfer (or review if rules already exist) to ensure that frameworks for sharing and leasing are fit for purpose in a world that will encompass both public mobile network operators and private LTE (and possibly other services making use of spectrum on a localised basis).
- The rules will need to be clear, provide regulatory certainty and enable a mechanism that is easy to use for private LTE operators seeking to access spectrum.
- Given the potential scale of private LTE (many instances of localised access), the rules need to avoid the creation of regulatory micromanagement. Micromanagement would increase both regulatory and industry costs and potentially become a bottleneck for those seeking access to spectrum for private LTE. Avoidance of micromanagement could include:
  - Provision of clear guidance for private LTE operators and mobile network operators on leasing of spectrum in harmonised bands.
  - The use of simple on-line registration processes and automation of responses where possible.
  - Minimising the need for and extent of ex-ante regulatory checks for mobile operator to non-mobile operator leases to reduce the burden for private LTE.

6.3 Disputes

There may be disputes between a private LTE operator and the entity from which it leases spectrum. Regulators may need to provide, as part of the guidance mentioned above, specific guidance on disputes. The lease should provide a mechanism to address disputes between lessor and lessee, with an appropriate escalation path. There should also be clearly defined parameters on the circumstances under which a regulator will become involved in a dispute and what the locus of the regulator is in these situations.

There may be aspects like contract terms, where regulatory input on fairness, for example, may be required. Some regulators already do this for consumer contracts by providing guidance, working to establish codes of practice or through establishing regulatory mechanisms (such as when switching from one operator to another or the ability to terminate contracts under certain conditions). It may be necessary to provide guidance on competition and unfair access terms in this respect.

6.4 Other issues

Operation of private telecommunications systems usually requires authorisation or licensing, in addition to spectrum authorisation. Exactly what is required will vary by jurisdiction, but it is something that operators of private LTE will have to address. This is not a new situation as, in many instances, private systems are already licensed (unless operating under an exemption). This may be through a class licence system or, as in the European Union, under General Authorisations. In some jurisdictions fees, in addition to what is paid for spectrum, may be applicable for the operation of private systems.

7 Conclusions

The conclusions of the research undertaken for this report are as follows:

- Access to harmonized mobile spectrum in required locations and on appropriate terms is key to the success of private LTE solutions that enable industrial automation.
- Dynamics of spectrum supply, in the case of private LTE, differ from the standard spectrum allocation from a government to an operator: The spectrum supplier (the MNO) must be incentivised to share spectrum and the demander (the private LTE network operator) must maximize the value realised from using the spectrum.
- Methods that could be applicable for valuation of spectrum for private LTE include:
  - Opportunity cost valuation, which will provide the MNO with a minimum price it should accept for sharing spectrum.
  - Business model, bespoke business analysis and valuation will provide the private LTE operator with an estimated value of spectrum.
- Provided the value placed on the spectrum by the private LTE operator exceeds the opportunity cost to the mobile operator, a market for private LTE spectrum should be possible.
- While spectrum sharing and/or leasing are the most likely methods for access to spectrum for private LTE, other market mechanisms can be considered for access to this spectrum including reserved spectrum for private LTE, wholesale spectrum provision and use of a spectrum broker.
- There could be other regulatory issues to address when operating private LTE networks, including:
  - Other licensing requirements for operation of telecommunications systems and any non-spectrum licence or authorisation fees payable.
  - Creation of simple regulatory processes to reduce the cost and minimise the complexity of use of spectrum for private LTE.
  - Provision of clear rules and guidance aimed at those wanting to supply and operate private LTE.

Appendix A Spectrum valuation methods

As discussed in Section 3, there are two main categories of valuation approaches – benchmarking and economic modelling. The mechanics of these methods are discussed in turn below. Note that while these are established methods for the valuation of public cellular mobile spectrum, there are problems with their application for private LTE as mentioned in Section 3.1.

A.1 Benchmarking methods

Benchmarking analysis is a common methodology for the valuation of mobile spectrum.[29] It involves a comparison of actual prices from spectrum auctions or trades for a selection of data points. The advantages of benchmarking analysis are that it is relatively simple and easy to understand as each data point reflects the actual amount paid by operators for spectrum and is verifiable because it is based on publicly available data. Prices paid in an efficient spectrum auction will generally reflect the value of an incremental spectrum lot to the marginal bidder – either the lowest value for a winning bidder or highest value for a losing bidder. In this sense auction benchmarks are arguably the most appropriate indicators of the market value of spectrum.

The key drawbacks of benchmarking are that data points from other countries may not reflect local market conditions in the country in question and because values vary between countries, the choice of the benchmark countries can significantly affect outcomes. Another issue relates to the strategic aspects of bidding, which may affect certain auction results. For example, a bidder may increase its bids to try to foreclose downstream competition by denying others of the spectrum they require, or to drive up prices paid by other bidders and thus inflating their competitors' costs. Therefore, benchmarking results need to be interpreted carefully to take account of specific circumstances.

A.1.1 Direct benchmarking

In the simplest direct benchmarking approach, values for a particular frequency band are used as benchmarks for the same band. Typically, the mean or the median are then used to derive an estimate of spectrum value, although the range of benchmark values is also useful as indicators of upper and lower bounds – although careful consideration of outliers is necessary.

In cases where there is a lack of benchmark data for specific frequency bands, a common approach is to rely on common band groupings by frequency, for example:

- Sub-1 GHz bands are often considered together as they have superior propagation characteristics that make them more valuable to mobile operators in terms of coverage and in-building penetration.

[29] While benchmarking is feasible for the valuation of mobile spectrum, it is less appropriate for the valuation of bands used for other services, such as broadcasting, land mobile radio, microwave links, or satellite services, due to the general lack of spectrum auctions for these services and the nature and licensing regimes of these services.

- The 1900 MHz (PCS) band, which is used in the Americas, is similar to the 1800 MHz band in Asia Pacific and Europe in terms of propagation characteristics and supports both 2G and 4G technologies.
- The 2100 MHz band used for 3G and increasingly 4G services in Asia Pacific and Europe is similar to the AWS bands in the Americas.
- The 2500 MHz or 2600 MHz band is globally harmonised for mobile services and can be considered a separate group. It is typically used as a "capacity" band – rather than to provide coverage – given its inferior propagation properties compared to lower frequencies. The 2300 MHz band has similar properties.

A.1.2 Adjusted benchmarking

Adjusted benchmarking is often used in cases where there are few actual data points in a frequency band for direct benchmarking. This approach involves the use of past auction results as **reference values.** There are two possible ways to carry out the adjusted benchmarking approach: the relative value method and the distance method.

In the **relative value method**, value ratios for the various frequency bands and band groupings are estimated from international benchmarks.[30] These ratios are then applied to the appropriate reference values to estimate the values for the different bands in question.

The **distance method**[31] makes use of observed distance ratios of selected reference bands relative to the band to be valued. These are calculated based on differences in value for selected bands from appropriate benchmark countries.[32] The distance ratios are then applied to the reference values in a particular country to estimate the value of the band in question.

A.1.3 Econometric analysis

Econometric analysis is a statistical method that provides an objective way of controlling for market and economic factors, and therefore offers a more promising way forward than simply taking values from other auctions. Moreover, there is less reliance on (often imperfect) comparisons between different countries. Instead, it uses the estimated relationships between observed spectrum prices and the explanatory factors (such as economic or demographic factors) to predict a value based on the economic and demographic circumstances in the country under study.

The goal of the econometric analysis is to estimate the value of spectrum (dependent variable) based on the effects of various drivers of spectrum value (independent variables) using data from a large number

[30] For example, the ratios used could be sub-1 GHz to 1800 MHz, sub-1 GHz to 2100 MHz, sub-1 GHz to 2600 MHz, etc.

[31] This method was used to estimate value of the 1800 MHz band in the UK. See Aetha-Analysys Mason. Review of Ofcom's benchmarking of the value of the 1800 MHz spectrum band to determine annual licence fees. Report for Three and EE, January 2014. http://stakeholders.ofcom.org.uk/binaries/consultations/900-1800-mhz-fees/responses/EE_Annex_Analysis_Mason_Aetha_report.pdf

[32] Values from at least three bands are needed.

of auctions. The potential drivers of value, which are typically considered in econometric analyses of spectrum value, are shown in Table A-1 below.

Table A-1: Potential drivers of spectrum values and variables

Potential drivers of spectrum value	Variables that can be considered
Spectrum characteristics	Frequency band or propagation, total bandwidth offered, time of auction, level of harmonisation
Licence characteristics	Licence duration, national or regional licences, coverage requirements
Auction characteristics	Ratio of bidders to winners, reserve prices, auction format, spectrum caps
Economic and market characteristics	GDP per capita, population density, mobile penetration, average revenue per user, fixed line penetration, number of mobile operators in market

While econometric analysis can be a more robust statistical method than the direct and adjusted benchmarking approaches, its reliability is affected by data availability and data quality. Numerous data points (ideally well over 50) are required to obtain robust parameter estimates. An econometric model's predictive power will also depend on how representative the sample is – in other words, whether it is appropriate to extrapolate from the known data points.

Also, while it is widely recognised that operators' strategic objectives (bidding strategy at auction and business strategy) and future expectations of the market are important drivers of spectrum values; information on these factors is not available in most cases. Furthermore, other factors such as spectrum caps, set-asides and coverage obligations attached to licences, are often defined differently across countries and so cannot be readily incorporated as dependent variables for the econometric analysis[33]. Given these limitations, econometric analysis should be considered alongside other benchmarking approaches as well as other valuation methods.

A.2 Avoided cost modelling

Another common methodology for spectrum valuation is avoided cost modelling.[34] This is based on the calculation of the potential cost reduction that a public mobile operator could expect if additional spectrum is available in its spectrum portfolio following an award process. The cost savings arise from the possibility of using the extra spectrum as a means of enhancing capacity or extending coverage without incurring the additional costs of physical infrastructure rollout. This is analogous to the

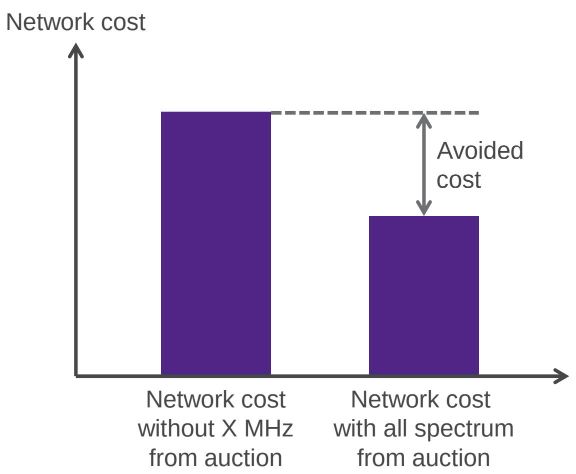
[33] It can be difficult to come up with a universally applicable definition for such factors. For example, coverage requirements may be defined by population, geography, or in some cases, by coverage of community centres and schools. Spectrum caps may relate to a specific auction, certain frequency bands or total spectrum holdings. While dummy variables may be used instead, they do not capture the full nature of these factors.

[34] This methodology is analogous to the least cost alternative (LCA) method which seeks to estimate the opportunity cost of spectrum and was derived by Smith-NERA in 1996 and refined by Indepen, Aegis Systems and Warwick Business School in a subsequent study for Ofcom. http://stakeholders.ofcom.org.uk/binaries/research/spectrum-research/spectrum_pricing.pdf

opportunity cost of the spectrum from the perspective of its use for the delivery of public mobile services.

The avoided-cost value of a particular spectrum band is calculated assuming that the operator views the spectrum as a marginal bandwidth. The operator first forms a view of the total bandwidth that it is likely to have in its portfolio in the long run, taking into account the opportunity to acquire new spectrum in an upcoming auction (or trade). The total cost of deploying and operating the network given this additional amount of spectrum is then computed. Subsequently, the spectrum band that the operator plans to acquire in the auction is removed (partially or wholly) from this portfolio, and a new network cost based on this new (reduced) spectrum portfolio is calculated. The network cost difference under the two spectrum availability scenarios represents the cost savings or the avoided costs as illustrated in Figure A-1.

Figure A-1: Illustration of the avoided-cost principle



The main network costs to be considered are those associated with the core network and the radio access network. The size of the core network is determined primarily by the total mobile data traffic that the network is expected to carry. The cost of the core network, thus, does not change under different spectrum assumptions, as long as the total traffic remains the same. Therefore, the cost difference between the two spectrum scenarios effectively becomes the difference in radio access network costs.

The costs of the radio access network under each spectrum scenario are calculated in three steps:

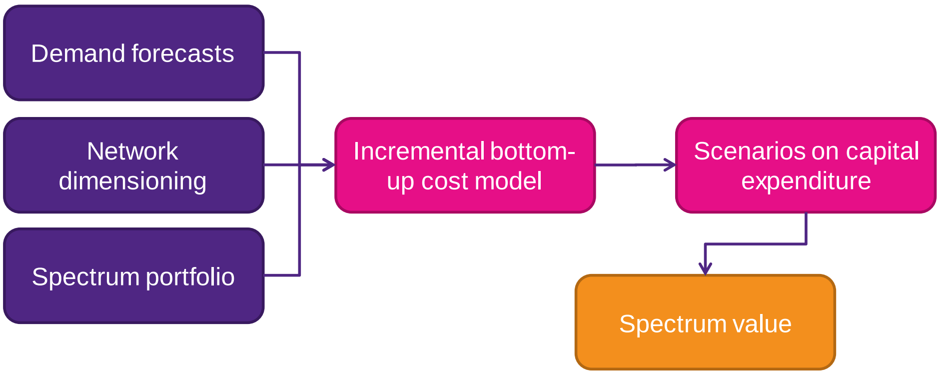
- **Demand determination** – This involves estimating an operator's mobile data traffic demand from the country's mobile data traffic based on the operator's market share in the different regions. The operator's regional traffic is in turn split across the different geotypes, which are defined by population density.
- **Network dimensioning** – The traffic for each geotype along with the operator's network roll-out plan and coverage obligations dictate the extent of the 3G and LTE physical infrastructure required in the radio access network. The number of 3G and LTE base stations and the

supporting backhaul connections are determined using these inputs, technical network parameters such as assumed transmission capability for each component, and the amount of spectrum available to the operator. The outputs from this step are the volume of infrastructure for each year of the spectrum licence period.

- **Network costing** – The annualised unit cost of each component on the 3G and LTE radio networks is then applied to the outputs from the network-dimensioning step to derive the implied total cost for each year of operation during the licence period. The annualised cost includes both CAPEX and OPEX. The total annualised costs are then discounted with an appropriate cost of capital and summed to compute the net present value of radio access network costs.

The steps described are shown in Figure A-2. As each operator's network and spectrum holdings will differ, avoided cost values are usually modelled for a "typical" operator and, if necessary, a "marginal" operator in a market.

Figure A-2: Steps for calculation of radio access network costs



There are a number of advantages to avoided cost modelling. The first advantage is that country-specific market factors as well as technology usage and developments can be directly accounted for. These factors can be set as parameters in the model and adjusted as required. In addition, depending on the requirements for the outputs, the model may be structured to provide costs by network component. This can be useful when sense checking for the implied expenditures against data from operators' reported network costs.

While the approach requires data on country-specific inputs, such as technical parameters that represent actual network operating conditions, some data may be collected by the regulator or reported by companies in annual financial reports. However, the data requirements are less onerous than business modelling, which requires information on revenue data and forecasts and other operating costs (such as marketing and staff wages). The business modelling method is discussed in Section 4.3 below.

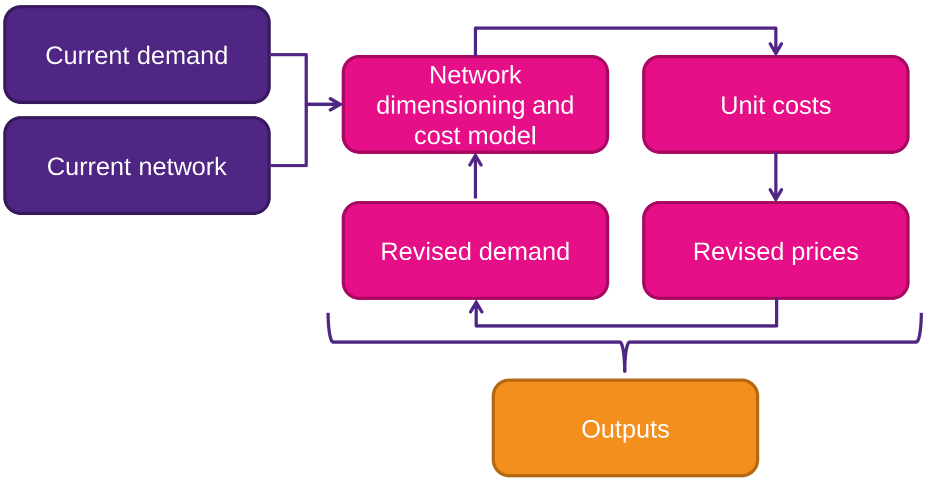
A.3 Iterative cost modelling

Plum has recently developed an **iterative approach** to complement the avoided cost modelling method[35]. This is an experimental approach which is currently being fine-tuned but has been used within the GSMA and as part of our work in for the Mexican regulator IFT. The iterative cost model provides an alternative way of thinking about data and spectrum demand by treating data demand as endogenous. In other words, consumers adjust their consumption of data in response to unit cost and price changes, rather than simply demanding the same quantity of data (regardless of the cost and price). On the supply side, operators expand network capacity as long as there is sufficient willingness to pay for the extra capacity.

One analogy of the iterative approach is road traffic planning[36]. Transport planners noticed that expanding road capacity did not solve the problem of congestion – instead, it increased the number of journeys until congestion was again a constraint. The extra road capacity lowers the 'cost' (in terms of time) of a car journey, so more journeys are made.

The iterative approach therefore incorporates a demand side assumption (consumers buy mobile data up to their willingness to pay) and a supply side investment decision rule, (only invest in capacity if willingness to pay for data exceeds the cost). The model is solved iteratively to find an equilibrium between data supply (capacity) and data demand as illustrated in Figure A.3 below.

Figure A.3: Illustration of the iterative approach



The core of the iterative cost model is similar to the avoided cost model, with a network dimensioning module calculating a network cost based on volumes and spectrum holdings. However, the iterative cost model takes the output of this central module to work out how unit costs would change following a change in spectrum holdings, uses this to define how demand would be affected, and feeds this into the central module a second time. This iteration is repeated a number of times (either a set number, or until an equilibrium is reached), and once an equilibrium is found, the impact of additional spectrum

[35] Plum (2014): "Do you need a mobile data forecast to estimate spectrum demand?" http://plumconsulting.co.uk/plum-insight-do-you-need-mobile-data-forecast-estimate-spectrum-demand/

[36] Litman (2012): "Generated traffic and induced travel – implications for transport planning." http://www.vtpi.org/gentraf.pdf

can be assessed by an avoided cost methodology (the additional spectrum reduces the cost of meeting the equilibrium level of demand).

There are several advantages to using an iterative approach. Firstly, it removes the need for a data forecast as an input (although an assumption on per-user expenditure is required). Secondly, the iterative approach significantly reduces the sensitivity of the results to changes in the input parameters. Finally, the economic framework of the iterative approach means some of the insights produced are qualitatively different to those produced under conventional approaches.

A.4 Business modelling

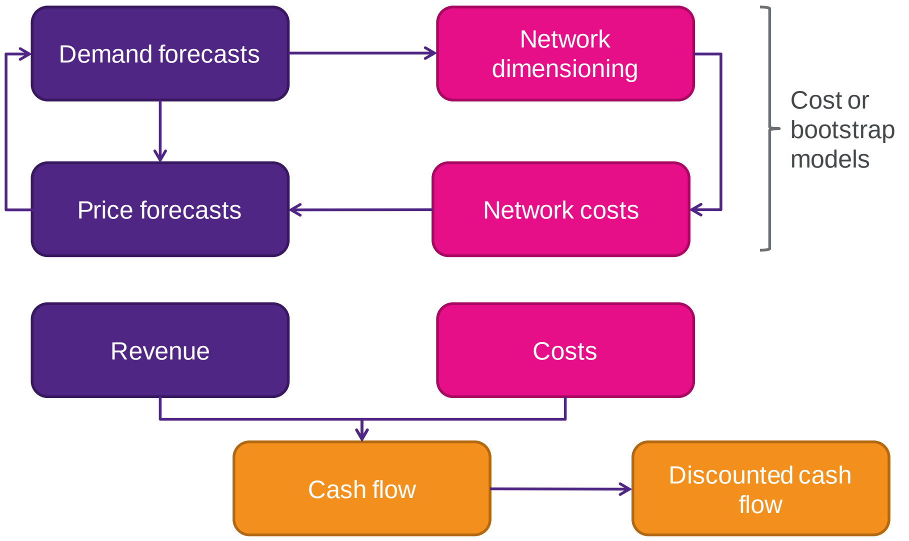
A business-based valuation model, also known as full enterprise valuation, assesses the value of spectrum from a commercial perspective. The objective is to understand how much profit the spectrum in question will generate for an operator over the licence duration. Estimating the value of spectrum involves the analysis of the impact on profits as a result of changes in spectrum fees over the modelling period. To derive the full enterprise value of spectrum, it is assumed that spectrum is a free input into the business.

A discounted cash flow (DCF) model is typically used and it involves two components.

- Revenue – total revenue estimated based on current and future demand (subscribers, ARPU), market circumstances (competition).
- Costs – network costs (radio access network, core network), non-network expenses (selling, general, administrative expenses, tax).

Figure A-4 provides a simple illustration of the DCF modelling approach.

Figure A-4: Illustration of DCF model



The net present value (NPV) of the profit stream for the operator is then calculated using its weight average cost of capital (WACC) and this is attributed to the operator's spectrum portfolio. The assumption is that all profits are derived from the use of spectrum, although in practice part of this value will be derived from other intangible factors (such as brand and the company's reputation to customers) that cannot be readily quantified. This NPV can be considered the full enterprise value of the spectrum and an upper bound on what the operator would be prepared to pay for the spectrum. A price higher than this level would mean the operator modelled would go out of business.

There are two key disadvantages with this approach:

- Information requirements: A significant amount of information is needed such as operators' business costs, market revenues and future business plans and strategies which will involve technology and market projections over the span of the spectrum licence. Assumptions may have to be made either using information from other markets or estimated based on existing sources, and views on competition, investment decisions and market and regulatory environments will need to be agreed on.

- It takes no account of the value of other intangible assets held by the operator – for example brand and customer value. These values could be significant and so mean the values obtained are far too high.