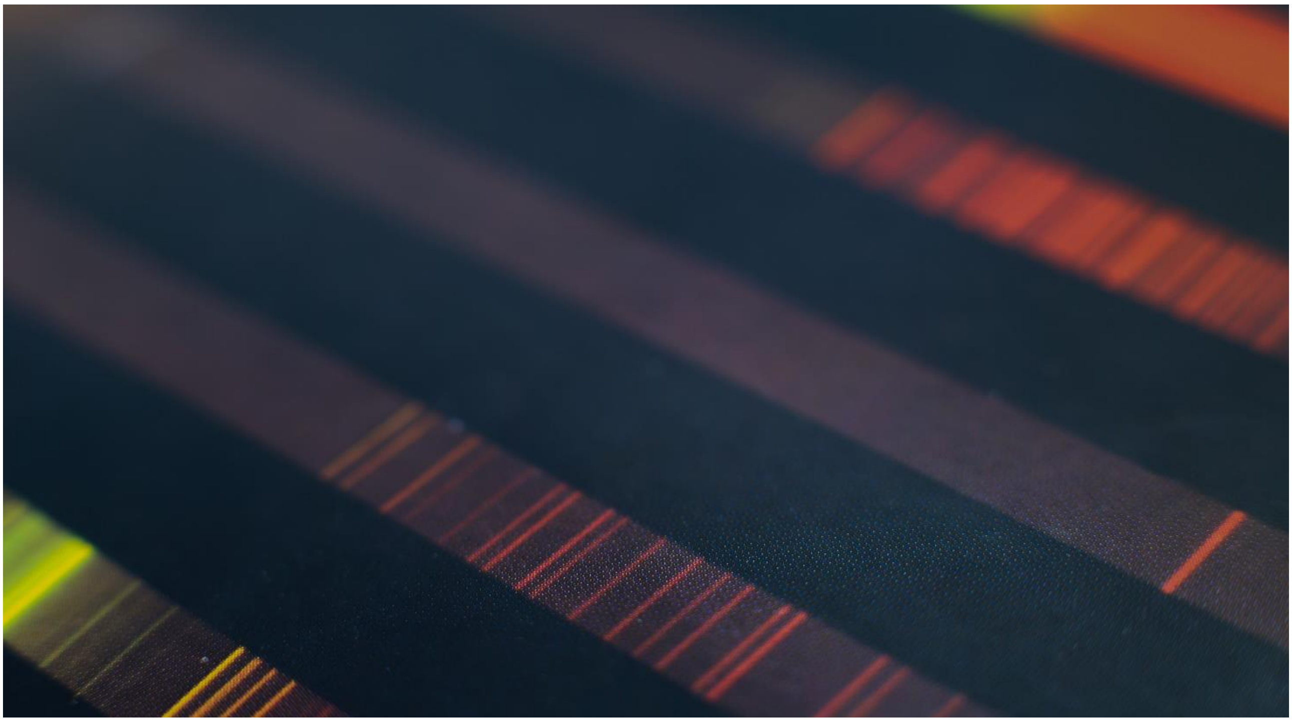
The defragmentation dividend

A more efficient use of the UHF band

White paper on behalf of Digital UK

November 2017



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0 Foreword

This report contributes to an emerging and important debate. It's a debate which UK policy makers initiated earlier this year and arguably is long overdue – not least as it could break the cycle of so-called 'spectrum wars' between our mobile and broadcasting sectors.

Tried and tested arguments are already being rehearsed ahead of World Radiocommunications Conferences in 2019 and 2023. Once again, sought-after UHF bands are a key battleground as two industries deploy evidence and lobbyists to demonstrate that on the one side demand for mobile data is surging; while on the other terrestrial television's role at the heart of our creative and cultural life is enduring. The simple truth is, of course, that both viewpoints are valid.

Our question to the team at Aetha was a simple one: "Is there a better way?" They have risen to the challenge and developed a response to growing demand for mobile data that goes beyond simply 'salami slicing' the spectrum used for terrestrial television. It's worth remembering that the latest example of this approach (the release of the 700MHz band across Europe) is taking more than five years to deliver at a cost of more than half a billion pounds in the UK alone. The Aetha team has developed ideas which could provide the mobile sector with significant gains from its existing spectrum while minimising the cost and disruption to other licenced users.

The ideas presented in this report are unashamedly ambitious. They originate in the UK but are of international relevance as every country attempts to meet an obligation to make the most efficient use of spectrum. The time horizon is deliberately long, reflecting the challenges not just for the mobile sector but also other users of the higher UHF bands, and the need to minimise incremental costs.

Sceptics may seek to dismiss Aetha's ideas as unrealistic or just too difficult. Such responses deserve to be challenged. If we are serious about moving on from the old ways of doing business, the proposals in this report deserve consideration as a potential win-win for those on both sides of this important debate.

This publication is just a first step. Taking these ideas forward, breaking with tired debates and overcoming obstacles will require determination and leadership. We hope UK policy makers are willing to engage with the possibilities presented here and use their influence to foster fresh thinking in the UK, Europe and beyond.

Jonathan Thompson, Chief Executive Officer, Digital UK

DigitalUK

1 Executive summary

Due to its excellent propagation, spectrum below 1GHz is a highly valued asset and is used to provide a variety of services, including digital terrestrial television (DTT) and mobile services.

Over the last 10 years, decisions have been made to clear broadcasting from two 'slices' of sub-1GHz spectrum across Europe so that they can be made available to mobile – first the 800MHz band and then the 700MHz band. The clearance process for the 700MHz band is on-going and due to be complete in the UK by 2020. Each instance has required substantial reconfiguration of DTT networks and in aggregate will reduce the spectrum available for broadcasting/PMSE from 368MHz to 216MHz. However, once complete, mobile operators will gain valuable capacity to meet the significant growth of mobile data services.

Ahead of WRC-15, there were further discussions to repurpose yet more broadcasting spectrum for mobile – including the possibility of a 600MHz band beneath 694MHz. The consequences of this would be an even more extensive DTT network reconfiguration and a reduction in the spectrum available for broadcasting (and PMSE) by a further ~35%, putting in question the entire feasibility of the DTT platform. At the same time, the benefit of such a small quantity of spectrum being made available for mobile may be modest – as 5G will require larger spectrum blocks. Ultimately, the Lamy Report[1] recommended security of tenure for broadcasting below 694MHz across Europe until at least 2030.

This period of certainty opens up the possibility of moving away from the well-trodden approach of repurposing small slices of spectrum from broadcasting to mobile and to instead consider a more holistic approach to the 470-960MHz range. Indeed, debates have been initiated at the UK and European levels about the long-term future of this spectrum, and specifically whether the existing allocations are fit for purpose over the long term[2].

The objective of this report, which has been commissioned by Digital UK, is to contribute to this discussion by considering options for the long-term use of the 694-960MHz range – i.e. the spectrum occupied by the three sub-1GHz mobile spectrum bands. Specifically, we have considered the possibility of creating a **'defragmentation dividend'** by reconfiguring the existing band plan between 694-960MHz to make additional capacity available to mobile services and other spectrum users. This increased capacity would be complemented by planned capacity improvements from DTT (e.g. a transition to DVB-T2) to ensure that the whole 470-960MHz range is used as efficiently as possible.

This report considers the long-term use of 694-960MHz primarily from a UK perspective. However, there are clearly wider considerations that should be taken into account – notably that it is infeasible for the UK to follow a new policy for 694-960MHz in isolation. That said, the findings of this report should also be applicable to Europe (and beyond), meaning that the UK's and Europe's standpoints may be aligned.

Current use of and future demand for 470-960MHz

The vast majority of the 470-960MHz range is used for broadcasting and commercial mobile services – with broadcasting (along with PMSE) occupying most of the spectrum below 694MHz and mobile the majority of the spectrum above 694MHz. However, there are a number of other services that also use this frequency range. In particular, there are a large number of licence-exempt users between 862-880MHz, which are predominantly short-range devices (SRDs).

It is likely that the spectrum demands of most of the current users of 470-960MHz will increase in the future. Whilst there may be a case for mobile to require more capacity, even after the 700MHz and 800MHz bands have been made available, there is also likely to be continued demand from broadcasting (to reflect the changing user requirements for higher-definition TV) as well as from other uses, especially SRDs and railway services (GSM-R). Consequently, clearing non-mobile services from the spectrum to make it available for mobile would have a significant opportunity cost.

It is also important to keep in mind that the requirements of the mobile sector are changing as it transitions towards new technologies. To fully exploit 5G and other future technologies, mobile operators will require large contiguous blocks of spectrum. Therefore, they should have limited demand for further assignments of small blocks of spectrum (e.g. 2×5 – 2×10MHz).

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[1] Pascal Lamy, Report to the European Commission, 'Results of the Work of the High Level Group on the Future Use of the UHF Band (470-790MHz)', August 2014.

[2] Notably, a debate was triggered on this topic during the European Spectrum Management Conference in Brussels in June 2017.

Figure 1-1: Potential defragmentation options

Options for further mobile capacity within 694-960MHz

Given the increasing demands for low-frequency spectrum from a variety of uses, we have developed three high-level 'defragmentation' options for the 694-960MHz range. The aim being to make more capacity available for both mobile and others, whilst trying to minimise the overall impact on all users. These options are summarised in Figure 1-1.

Option 1 increases the capacity available to mobile-based services whilst continuing to rely on FDD technology[3]. In contrast, Option 3 represents a significant departure from the status quo as it includes only a single large TDD band – which maximises the capacity provided to mobile-based services. Option 2 can perhaps be considered a compromise solution. Whilst ultimately transitioning to TDD, this option leaves certain existing uses untouched (e.g. licence-exempt use from 863-875MHz). It also offers the option for a transitional arrangement for mobile services, by temporarily leaving the 900MHz band intact – at least, until sufficient users have migrated to the newly created TDD solution in lower parts of the frequency range.

The benefits in terms of incremental low-frequency capacity for mobile-based services vary between the three defragmentation options, as illustrated in Figure 1-2. Option 3 would provide an additional 70% of downlink capacity, whilst Option 1 would provide a more modest 25%. However, to put these figures in context, even the more modest increase of 25% in Option 1 would be similar to the capacity that could be provided by repurposing the 600MHz band. Note that these figures are incremental to capacity improvements that will be made in any case as a result of network upgrades and technological improvements

Figure 1-2: Potential capacity gains

Defragmentation option	Mobile/PPDR/ GSM-R spectrum	Increase in DL capacity[4]
Current situation (post 700MHz)	218MHz	-
1 – Large FDD band	235MHz	~25%
2 – Three TDD bands	235MHz	~60%
3 – One TDD band	250MHz	~70%

It is also important to keep in mind that this additional capacity may also be used for other mobile-based services such as PPDR and GSM-R.

Capacity gains are not the only benefit of defragmentation. A defragmented band plan would provide mobile operators with

[3] Annex B explains frequency division duplex (FDD) and time division duplex (TDD) technologies in a non-technical manner.

[4] Calculated as: the downlink capacity in the scenario (assuming that 100% of FDD downlink spectrum and SDL spectrum provides downlink capacity and 80% of TDD spectrum provides downlink capacity) divided by the downlink capacity post-700MHz implementation.

larger contiguous blocks of spectrum that are more suited to 5G, a simplified network leading to cost savings (as fewer bands are in operation), and there would be a reduced requirement to clear spectrum from other uses (including broadcasting) to make way for mobile services.

Naturally, carrying out a defragmentation would be a complex task – and a range of technical, regulatory, and commercial obstacles would need to be overcome. However, examples such as the 700MHz and 800MHz clearances show that transitions of this scale can be achieved. One notable constraint is that the UK is not a sufficiently large market to adopt a new mobile band plan in isolation. Therefore, the case for defragmentation is contingent on a substantial market (e.g. the EU) adopting it. Whilst our analysis of existing and future uses has been focused on the UK, we expect that the EU (and potentially other markets) would see similar benefits to defragmentation given the similarity of current spectrum assignments.

Other notable constraints include:

- Much of the capacity gains from defragmentation are generated through the use of TDD technology. Whilst TDD is yet to be used below 1GHz, we expect this to change, especially given the experience that will be gained in the coming years from the use of TDD in higher-frequency bands.
- Legacy mobile devices and other existing uses (especially PMSE, SRDs, and IoT devices) may need to be migrated to new frequencies. However, provided that sufficient notice is given, the cost of such migrations can be minimised.

The main cost and benefit categories for each of the potential options are illustrated in Figure 1-3.

Figure 1-3: Summary of costs and benefits

	1-Large FDD band	2 - Three TDD bands	3 - One TDD band
Incremental capacity	+	++	+++
Future-proof holdings	+	++	+++
Reduced impact on broadcasting	+	+	+
Transitional licencing?	o	o	o
Technical constraints?	+	o	o
Migration costs	–	o / –	– – –

The intention for this report is not to identify an optimal defragmentation solution; further study will be required to do that. However, the analysis of the above three options highlights that there is a trade-off between the additional capacity provided to mobile-based services and the costs to migrate other non-mobile users. Notably, any solution that requires the migration of SRDs in the 863–870MHz range substantially increases the cost of implementation.

Recommendations for UK policy makers

Based on the analysis presented in this report, we believe that a 'defragmentation dividend' offers an interesting and credible long-term solution to increase capacity for mobile-based services. Therefore, we recommend that further study is conducted to fully explore the defragmentation options available as well as the merits of each proposed solution.

Given that the case for defragmentation in the UK is contingent on the EU (or another substantial market) also opting for a defragmentation, we recommend that UK policy makers engage with their European/international counterparts to ensure that defragmentation is further evaluated and given appropriate consideration in fora that discuss the future of 470-960MHz. Notably, we recommend that UK policy makers:

- Raise the concept of defragmentation within the RSPG and with the European Commission and recommend that EU-wide assessments are conducted.
- Influence CEPT's position ahead of WRC-19, such that the future use of 694-960MHz (including a potential defragmentation) factors into discussions at WRC-23, rather than the focus solely being on 490-694MHz.

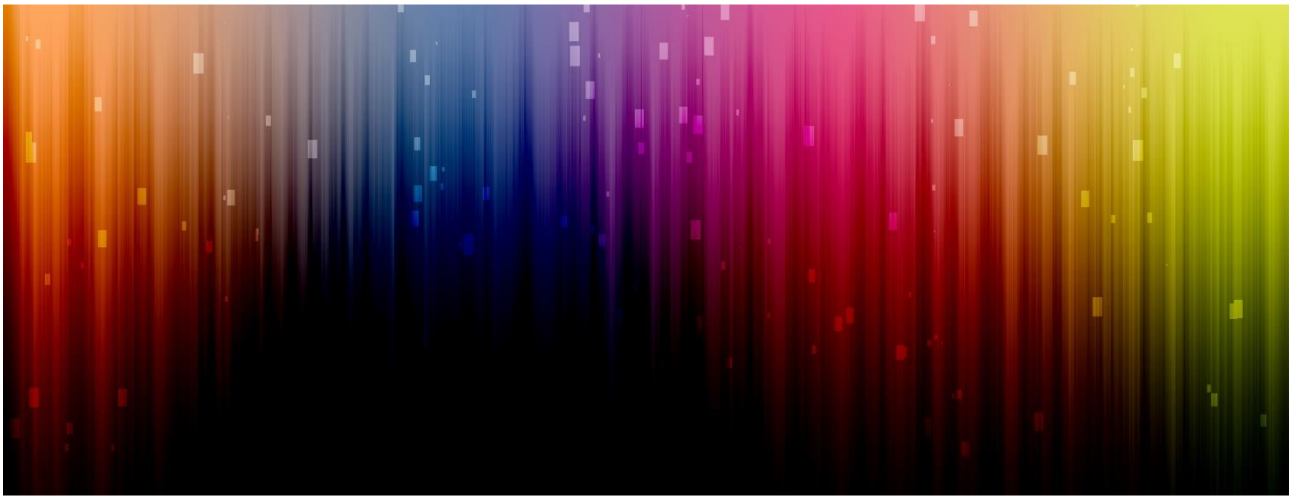
2 Introduction

Ensuring efficient spectrum use is a key goal for spectrum managers. As stated by UK regulator Ofcom on its website *"One of Ofcom's roles is to manage the radio spectrum so as to ensure that it is used in the most efficient and effective way for the benefit of the UK."* [5]

One of the most valuable spectrum assets is low-frequency spectrum, which is typically defined as spectrum below 1GHz. Due to its excellent propagation characteristics, this spectrum offers the opportunity to provide wide-reaching coverage at limited cost. It is used by a variety of services: by the broadcasting sector to deliver nationwide coverage of digital terrestrial television (DTT), by mobile network operators (MNOs) to provide nationwide coverage and also by rail networks, programme making and special events (PMSE) and many other users. Given the wide array of wireless services requiring access to this spectrum, it should be a priority to ensure that it is used as efficiently and effectively as possible.

Low-frequency spectrum allocations have been the subject of many intense debates – both at a national and international level. Over the last 10 years, the significant take-up of mobile data services has provided the rationale for two new bands to be 'sliced off' broadcasting spectrum and made available for mobile services – the 'digital dividend' 800MHz band and more recently the 700MHz band. Ahead of WRC-15, discussions took place to assess whether even more low-frequency spectrum, e.g. a 600MHz band below 694MHz, should also be made available for mobile services. However, the Lamy Report[6] recommended security of tenure for broadcasting services below 694MHz across Europe until at least 2030. This was confirmed at WRC-15, where a co-primary allocation for mobile services below 694MHz was not granted in ITU Region 1 and where it was recommended that a general discussion on the use of the frequency range 470-960MHz should be postponed until WRC-23.

Whilst the allocation of more spectrum to mobile services below 694MHz is thus not a short-term possibility, there is merit in reviewing the proposals that were made. A number of different options were assessed, one of which was the creation of a 600MHz band. This would have followed the same approach as previously taken, namely to make available another 'slice' of spectrum to mobile services, similar in size and configuration to the 700MHz and 800MHz bands. This would have likely created a 'lose-lose' situation for all affected parties. Mobile operators would have been left with a small sliver of spectrum, unsuitable for 5G and only providing a modest uplift in capacity. At the same time, it would have meant a significant reduction in the spectrum available to broadcasting as well as PMSE. At best, this would have created large network reconfiguration costs. At worst, losing access to further spectrum would have put in question the feasibility of the DTT platform as a whole.



5 See https://www.ofcom.org.uk/about-ofcom/annual-reports-and-plans/spectrum-management-costs-and-fees.

6 Pascal Lamy, Report to the European Commission, 'Results of the Work of the High Level Group on the Future Use of the UHF Band (470-790MHz)', August 2014.

Given the recent political decisions outlined above, significant changes to spectrum allocations within 470-960MHz will not occur for a period of more than 10 years – until 2030 at the earliest. This extended period of certainty offers a unique opportunity to move away from the well-trodden approach of making available small (and increasingly unusable) slices of spectrum, and instead embrace a more holistic approach to spectrum below 1GHz. Indeed, a debate on this topic was initiated during the European Spectrum Management Conference in Brussels in June 2017.

The aim of this report is to make a contribution to this discussion. Aetha has been commissioned by Digital UK to consider options for making more capacity available, specifically within 694-960MHz – i.e. the spectrum occupied by the three sub-1GHz mobile spectrum bands. The aim is to trigger further debate regarding the use of this frequency range to complement ongoing discussions regarding 470-694MHz, enabling an informed discussion on the whole 470-960MHz range, as envisioned for WRC-23.

Our specific contribution is the proposal for a re-organisation (in fact, a de-fragmentation) of the current mobile band plans in order to create significant extra capacity for mobile as well as other services. We term the resulting increase in capacity the **'defragmentation dividend'**.

The increased capacity generated from defragmentation would be complemented by planned capacity improvements from DTT (e.g. a transition to DVB-T2) in order to ensure that the whole 470-960MHz range is used as efficiently as possible.

It is important to keep in mind that all proposals outlined in this report have to be considered over a long-term perspective, i.e. for implementation from 2030 at the earliest. We do not believe that they can be introduced in the short term. However, given the time available in light of recent WRC decisions, we believe that now is the ideal time to consider the options available, otherwise a unique window of opportunity could be missed.

Moreover, the conclusions of this study should be viewed as initial high-level proposals. Whilst we discuss the benefits, costs and constraints of our proposals in some detail, additional work needs to be undertaken by the appropriate bodies to assess potential issues associated with our proposals and to ensure that any interference, migration or co-existence concerns can be analysed and resolved as required.

The focus of this study is on the use of low-frequency spectrum in the UK. However, the benefits of a defragmentation dividend can only be realised through economies of scale across a wider geographic area – at least Europe, but ideally a number of ITU regions. Although there are some differences in the conditions and spectrum allocations in other European countries, we believe that the overall situation is sufficiently similar to the UK that many of the findings in this report should be applicable in a wider European context.

In order to introduce our options for a 'defragmentation dividend', the remainder of this report is structured as follows:

- Section 3 analyses the current and planned use of spectrum in the frequency range 470-960MHz.
- Section 4 assesses the future demand from a range of services for spectrum from 470-960MHz.
- Section 5 introduces different options for realising a 'defragmentation dividend' and discusses the associated benefits, costs and constraints.
- Section 6 summarises the main conclusions from the report.

In addition, we have appended a number of annexes to this report, which discuss the technical aspects underlying our analysis in more detail.

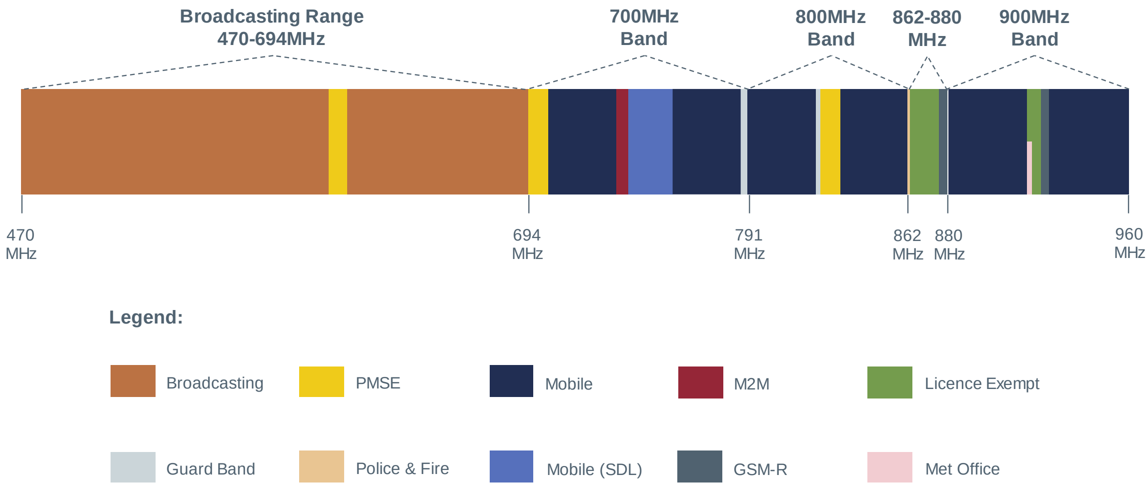
3 Current and planned use of 470-960MHz

In this section, we outline the current and planned use of 470-960MHz in the UK in order to identify all parties that may be affected by a defragmentation dividend.

We have split the range into five sections - the 'broadcasting range' (470-694MHz), the 700MHz band (694-790MHz), the 800MHz band (790-862MHz), the 'licence-exempt range' (862-880MHz) and the 900MHz band (880-960MHz).

These ranges are presented in Figure 3-1 below. Please note that we have based all assumed future allocations on Ofcom's latest statements – this is particularly relevant for the 700MHz band.

Figure 3-1: Overview of spectrum allocations in frequency range 470-960MHz in the UK



3.1. The broadcasting range (470-694MHz)

This frequency range is largely used for the provision of DTT services. Six nationwide multiplexes (MUXes) are operated across the UK as well as local MUXes and the Northern Ireland MUX. Notably, as a result of the recommendations from the Lamy Report[7], there is security of tenure for broadcasting within this frequency range until, at least, 2030.

In addition to DTT, there are a number of users with secondary allocations. Some of the spectrum is used by PMSE, particularly in 606-614MHz ('Channel 38') but also on an interleaved basis across the broadcasting range. This is primarily utilised by wireless microphones, as well as other audio links. White space devices (WSDs) are also able to utilise the entire frequency range on a secondary, licence-exempt basis. We do not believe that there are significant numbers of WSDs currently operating in the UK, but applications include the provision of broadband connectivity in rural communities, wireless connectivity on campuses and Internet of Things (IoT) applications.

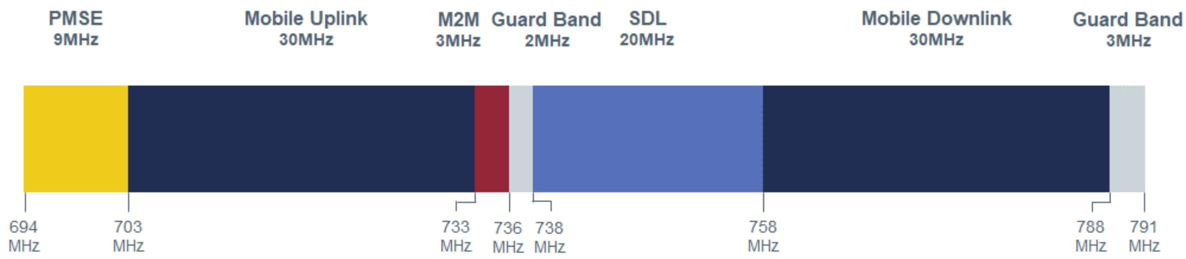
3.2. The 700MHz band (694-791MHz)

Currently, the 700MHz band is largely dedicated to the provision of DTT services, similar to the 470-694MHz range. However, Ofcom has decided to make this band available for mobile use by May 2020, in keeping with other EU countries[8]

[7] Pascal Lamy, Report to the European Commission, 'Results of the Work of the High Level Group on the Future Use of the UHF Band (470-790MHz)', August 2014.

[8] European Commission, 'European Commission – Press Release: Commission welcomes political agreement to boost mobile internet services with high-quality radio frequencies', December 2016.

Figure 3-2: Planned 700MHz configuration



This requires the relocation of DTT and PMSE services, the costs of which are estimated at GBP550-600 million[9]. Conversely, the benefits of making the spectrum available to mobile use are estimated at GBP900-1300 million, derived mainly from improved coverage in rural areas and economies of scale for device manufacturers[9]. The likely future configuration of the 700MHz band is presented in Figure 3-2.

The main part of the 700MHz band is an allocation of 2×30MHz for mobile use. Furthermore, Ofcom has identified 20MHz in the centre gap for mobile use as supplementary downlink (SDL). Ofcom further announced a consultation on the possibility of allocating 3MHz of the remaining centre gap to Machine-to-Machine (M2M) services. The guard band at the bottom of the 700MHz band (694-703MHz) has been designated by Ofcom for PMSE users. In contrast to other European countries (e.g. France), there is no allocation of spectrum for Public Protection and Disaster Relief (PPDR). This is due to plans to use EE's commercial mobile network for the emergency services network (ESN).

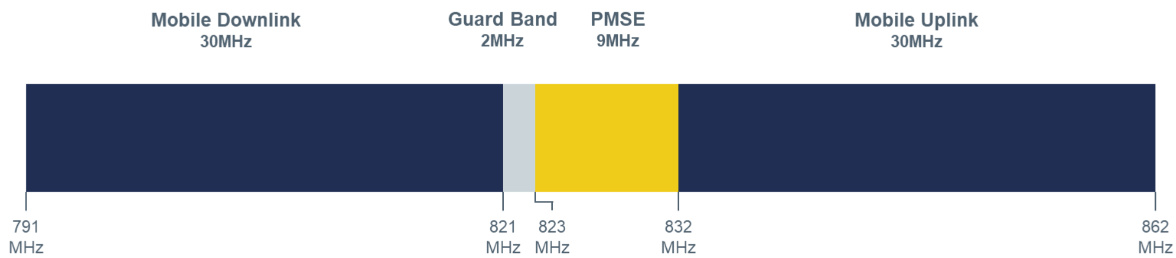
3.3. The 800MHz band (791-862MHz)

The 800MHz band was made available for mobile broadband services in 2013, following the decision to grant a co-primary allocation to mobile services after the digital switch-over of broadcasting services to DTT. A total of 2×30MHz is available for MNOs and the spectrum is being used to deliver 4G coverage across the UK.

Spectrum in the 823-832MHz duplex gap is used by PMSE following a decision by the European Commission in 2014[10] to harmonise this spectrum for PMSE across Europe, with the intention of enabling economies of scale. PMSE applications are limited to audio devices (e.g. wireless microphones).

The resulting configuration of the 800MHz band is presented in Figure 3-3 below.

Figure 3-3: Current configuration of the 800MHz band



9 Ofcom, 'Decision to make the 700MHz band available for mobile data', November 2014.

10 European Commission, 'Commission implementing decision on harmonised technical conditions of radio spectrum use by wireless audio programme making and special events equipment in the Union', September 2014.

3.4. The licence-exempt range (862-880MHz)

The bottom 1MHz (862-863MHz) is used by the police and fire services to operate communications systems, the licences for which are assigned at brigade/force level. Ofcom has previously considered re-allocation to very low duty-cycle SRDs. This use should thus not be a large barrier to defragmentation.

Spectrum from 863-876MHz is allocated to licence-exempt use, mainly Short-Range Devices (SRDs) such as home automation, alarm, automotive, industrial, audio and Radio-Frequency Identification (RFID) applications. The band is extensively used, as noted in a 2012 report by the ECC[11] , which found that more than 10 million metering devices, 10 million home automation devices and 10 million alarm systems operate within 863-870MHz across Europe.

GSM-Railway (GSM-R) uses 876-880MHz (paired with 921-925MHz). A GSM-R network was rolled out across the UK from 2007-2014, requiring a total investment of GBP1.86 billion[12]. There are international discussions regarding a migration from GSM-R to an LTE-based solution, known as the Future Railway Mobile Communication System (FRMCS), but, given the comparatively nascent investment in GSM-R, imminent implementation in the UK is unlikely.

3.5. The 900MHz band (880-960MHz)

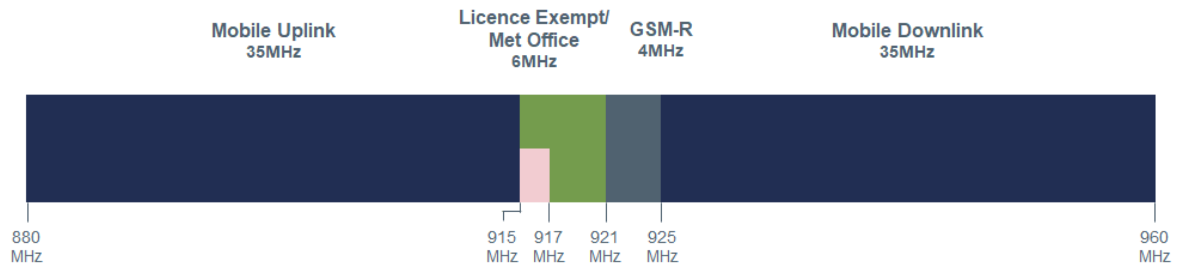
The 900MHz band is largely occupied by mobile applications. A total of 2×35MHz (880-915MHz and 925-960MHz) has been used by MNOs to operate GSM (2G) services across Europe since 1991. Whilst currently used for 2G and 3G technologies, it is a potential candidate for future 4G/5G deployments.

The duplex gap (915-925MHz) is allocated to several other uses. As mentioned above, GSM-R utilises spectrum in 921-925MHz for downlink. In addition, 915-921MHz was made available, along with 870-876MHz spectrum, for licence-exempt use in 2014. This spectrum coincides with an Industrial, Scientific and Medical (ISM) band in ITU Region 2. Given the benefits of economies of scale, especially for RFIDs, this could lead to a large increase in the number of deployed devices in the future.

The Met Office also utilises spectrum from 915-917MHz to operate Wind Profiling Radar (WPR). However, use in this band is limited to two sites, which share use with licence-exempt devices[13] .

The resulting configuration of the 900MHz band is presented in Figure 3-4.

Figure 3-4: Current configuration of the 900MHz band



[11] Electronic Communications Committee, 'ECC Report 182, Survey about the use of the frequency band 863-870MHz', September 2012.

[12] Network Rail, 'Guide to the GSM-R System', Available at https://16cbgt3sbwr8204sf92da3xxc5m-wpengine.netdna-ssl.com/wp-content/uploads/2017/06/Network-Rail-Telecoms-briefing-pack.pdf.

[13] Met Office, 'Met Office response to Ofcom Consultation: 870-876 &915-921MHz – Update and Way Forward', 2013.

3.6. Summary of current and planned spectrum use

Low-frequency spectrum is being used by a wide range of services in the UK:

- Spectrum below 694MHz is allocated to broadcasting on a primary basis and is used extensively for the provision of DTT and PMSE services.
- The majority of the remaining spectrum has been (or will be) made available for mobile services – the 800MHz and 900MHz bands are already in use, whilst the 700MHz band will be in the near future.
- GSM-R uses 2×4MHz.
- PMSE has access to a number of frequencies. Some of these are already in heavy use (Channel 38, interleaved spectrum) whereas others will only be made available in the future (e.g. 694-703MHz).
- Licence-exempt services can also make use of a number of smaller frequency ranges – again, some of these are already in heavy use (863-876MHz), whereas others have only been identified more recently.
- There are also some smaller allocations (e.g. to Met Office, Police & Fire services), but these are not used as extensively.

In the context of a potential defragmentation of 694-960MHz, it may be challenging to free up certain parts of the band. This may particularly be the case for the licence-exempt spectrum in 862-876MHz, due to the difficulties of identifying and then moving the large numbers of existing users. In contrast, use of the various duplex gaps in the 700MHz, 800MHz and 900MHz bands is limited at present, implying that changes to these spectrum allocations are feasible as long as they are made prior to significant service take-up. We will discuss such constraints further in Section 5.3 below.

4 Future spectrum demand in 470-960MHz

In this section, we outline the likely future demand for spectrum in 470-960MHz and highlight the issues that should be considered when assessing potential changes to spectrum allocations in this range.

There will be continued demand for spectrum in 470-960MHz from a range of users, including DTT, GSM-R, IoT/SRDs and mobile services. Whilst a quantification of this demand is outside the scope of this report, this section qualitatively discusses the factors that drive spectrum demand for each service.

Note that, due to the commercial arrangements being put in place for the provision of a PPDR network in the UK, we do not discuss this service in this section.

4.1. Digital Terrestrial Television (DTT)

There are both technology and consumer trends in the DTT market that are expected to influence spectrum demand over the coming years, including[14]:

- new digital formats – such as Ultra-High-Definition (UHD)
- transmission and encoding developments – such as DVB-T2, MPEG-4 and HEVC[15]
- complementary or alternative platforms to DTT – such as IPTV or Hybrid Broadcast Broadband TV
- trends in future demand for linear TV broadcasting, and the economics of different distribution mechanisms in fulfilling this demand.

The number of HD channels available in the UK is increasing and is expected to continue to do so. An HD channel requires approximately 150%[16] more capacity than a standard-definition (SD) channel. As consumers increasingly demand DTT content to be available in HD format, whilst expecting the same range of channels to be available, spectrum demand for DTT is set to increase. The same logic applies to UHD and, possibly, 3D services, further adding to DTT spectrum demand.

[14] Changes to infrastructure models, such as single-frequency networks (SFNs), also have the potential to influence spectrum demand. However, due to significant barriers to the adoption (e.g. high network migration cost, concerns regarding network coverage levels), we do not expect such models to be adopted prior to 2030.

[15] High-Efficiency Video Coding, a new video encoding standard that significantly increases the compression efficiency compared to previous standards.

[16] Analysys Mason, Report for the European Commission, 'Spectrum Policy – Analysis of technology trends, future needs and demand for spectrum in line with Art.9 of the RSPP', 2013.

Conversely, developments in transmission and encoding may reduce spectrum demand. Previously, DVB-T has been used across Europe, enabling bitrates of 8-27Mbit/s per MUX.16 However, in the UK DVB-T2 technology has been introduced to a subset of MUXes, enabling bitrates of up to 40 Mbit/s per MUX; a 30% capacity increase. MPEG-4 compression technology is expected to be implemented in parallel with DVB-T2, replacing MPEG-2. Looking further ahead, HEVC technology might be incorporated, offering a compression increase of 70% relative to MPEG-2.16 Of course, during any transition period there will be a need to simulcast using both the new and legacy technologies, temporarily increasing the capacity required. However, all these technological changes should ultimately lead to more capacity being available on the DTT network.

Alternative TV platforms could emerge and reduce the requirement for broadcasting to rely on the terrestrial network to provide universal services. IPTV is sometimes mentioned as a suitable future platform to replace DTT. However, IPTV deployments in the UK to date have been used to complement rather than substitute DTT, with several services using hybrid DTT/IP technology (e.g. YouView, EETV, NowTV, Freeview Play). It remains unclear whether there will be sufficient investment in broadband access networks in the future to provide ubiquitous access to IPTV services. As a result, DTT is likely to remain the only means to provide linear services with ubiquitous coverage in the foreseeable future.

In conclusion, there are counter-balancing factors driving spectrum demand for TV services, as demand for increasingly higher-definition TV is (partially) offset by improvements in broadcasting technology. As a result, it is unlikely that spectrum demand for broadcasting services will reduce significantly – a view corroborated by the European Commission[16], which in fact predicted that spectrum demand for broadcasting may exceed current European allocations in the medium to long term.

4.2. GSM - Railway (GSM-R)

The GSM-R roll-out in the UK was only completed in 2014 at a cost of GBP1.86 billion12. The rail industry has committed to supporting GSM-R until at least 2030. Nevertheless, the International Union of Railways (UIC) set up the Future Rail Mobile Communications System (FRMCS) project in 2012 to prepare for a transition to an LTE-based solution, roll-out of which is expected to begin around 2023 at the earliest.

Given recent investments, spectrum demand for GSM-R is likely to persist for the foreseeable future. This may be supplemented by additional demand to support a transition to LTE-based technology, with spectrum demand being particularly high during the migration period (estimated at 2×7MHz[17]).

4.3. Internet of Things / Short Range Devices

The rapid growth in the Internet of Things (IoT) / Short-Range Device (SRD) market is widely expected to continue, including areas such as:

- RFID: The European Commission predicts the RFID market to reach a global value of EUR15-20 billion by 2018, 20% of which would be in Europe. [18] In order to meet this demand, Ofcom made the 870-876MHz and 915-921MHz ranges available for licence-exempt use in 2014. [19] The 915-921MHz range is particularly valuable as it coincides with an ISM band in ITU Region 2.

- Alarm systems: Whilst a growing number of devices are based on wireless systems (e.g. 600 000 new intruder-alarm installations are expected in the UK per year[20]), it is unclear whether the overall spectrum requirement will increase significantly given the way in which the systems are used.

- M2M: M2M covers an array of applications, for example in the building automation, utilities and automotive sectors. Logistics and manufacturing rely on SRDs for identification of parts, tracking by RFID and automation of factory processes whilst automotive applications include tyre-pressure monitoring and proximity sensors. A 2013 Ofcom report identified 149 M2M applications and estimated that 350 million M2M connections would be present in the UK by 2022, 15-74% of which could be served with short range technologies. [21]

[17] UIC, 'NG2R(16)006011r2: FRMCS Spectrum Demand Calculation', September 2016.

[18] European Commission, JRC Technical and Scientific Reports 'RFID: Prospects for Europe', October 2010.

[19] Ofcom, 'Authorisation of Short Range Devices in 870 to 876 MHz and 915 to 921 MHz, April 2014.

[20] Plum Consulting, 'Future use of Licence Exempt Radio Spectrum', July 2015.

[21] Aegis and Machina Research, 'M2M application characteristics and their implications for spectrum', May 2014.

However, it is unclear whether this growth in devices will impact spectrum demand over the coming years. Technology developments are expected to optimise the use of existing spectrum by SRDs and allow them to operate in frequency ranges where use is currently restricted to licensed applications (e.g. using geo-location databases). For example, since 2015, Ofcom has made 470-790MHz available for use by WSD. Finally, many SRDs are either used in very restricted geographic areas (e.g. alarm systems) or require only limited bandwidth (e.g. devices on low-power wide area networks such as Sigfox).

Nevertheless, the European Commission predicts an increased spectrum demand for IoT/SRDs in the short, medium and long term[16]. Ofcom has declared that its decision to allow licence-exempt use in 870-876MHz and 915-921MHz, as well as the 470-790MHz frequency range (AC-WSDs) should meet IoT's short-term to medium-term spectrum demands[22].

4.4. Mobile services

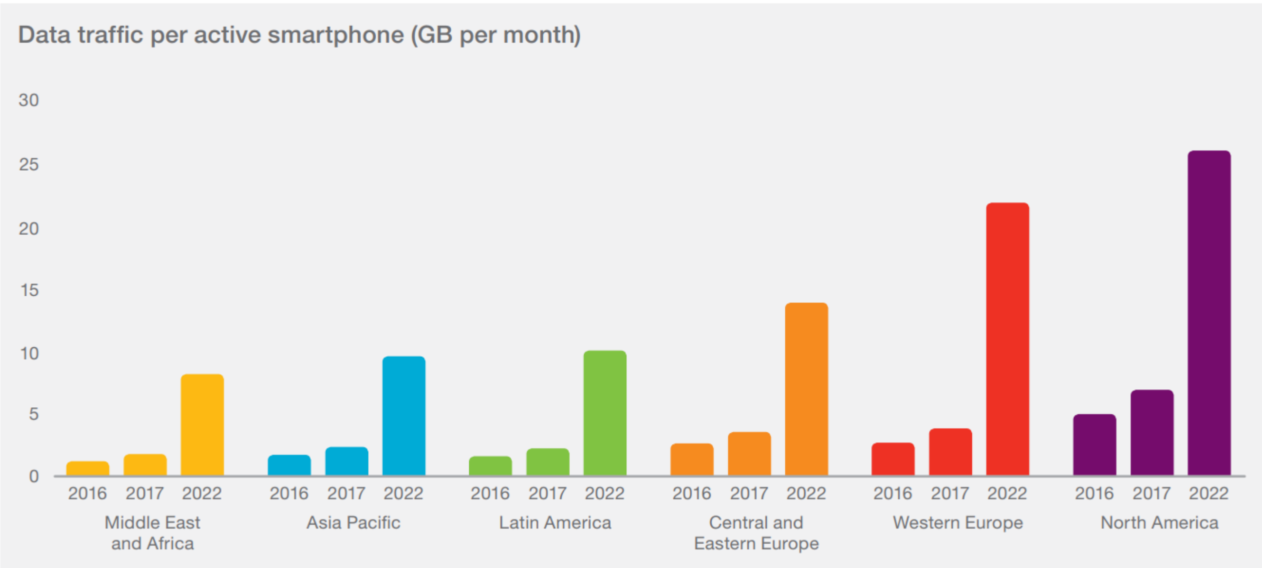
Demand for additional capacity on mobile networks in recent years has been primarily driven by the increased take-up of data services, a trend which is expected to continue in the coming years. Ericsson[23] estimates that global mobile data traffic will increase eightfold from 2016-2022, with data traffic generated by smartphones increasing tenfold (is illustrated in Figure 4-1 below).

In the UK, recent traffic trends mirror those observed internationally. Between 2015 and 2016, mobile data consumption per user increased by 49%. The corresponding figure for the period 2014/15 was 64%[24].

The expected increase in demand for mobile services will in turn mean that demand for additional capacity on mobile networks will increase. However, it is important to acknowledge that this need for more capacity does not necessarily translate into a direct need for more spectrum. Additional capacity can be provided by several means – of which spectrum is just one option. Alternative options for mobile operators to increase capacity include, amongst others:

- installing additional base stations (e.g. small cells)
- re-farming existing spectrum from 2G or 3G legacy services to newer technologies
- deploying the latest hardware features (e.g. by upgrading antenna systems to higher-order MIMO).

Figure 4-1: Smartphone data traffic forecast [Source: Ericsson, 'Ericsson Mobility Report 2017']



[22] Ofcom, 'Ofcom sets out plans to support the Internet of Things', January 2015.

[23] Ericsson, 'Ericsson Mobility Report', June 2017.

[24] Ofcom, 'Connected Nations 2016', December 2016

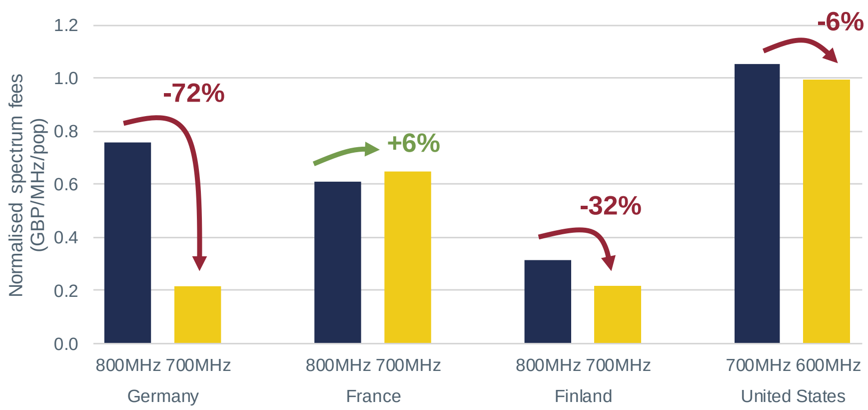
Given the range of options available to mobile operators to increase network capacity, it is important that any additional spectrum is made available in a way that best addresses the operators' needs. In light of recent technology trends, the following aspects should be considered:

- 5G readiness / speed: To fully realise the potential of future technologies such as 5G, large carrier sizes are required (at least 20MHz, ideally up to 100MHz).[25] However, operators typically hold at most 2×10MHz in the various low-frequency bands. Whilst the UK's 900MHz assignments are a notable exception to this, the 800MHz band was split across four operators.
- Network management / cost: With an increasing number of bands being made available to mobile operators, management of networks is becoming increasingly costly. Deploying additional spectrum bands typically requires extra capital expenditure (e.g. the cost of installing the relevant equipment) as well as ongoing operating expenses (e.g. increased power costs). Operators are thus likely to prefer gaining access to larger blocks across fewer bands.
- Bandwidth management / efficiency: Data traffic is highly asymmetric, as 85-90% of all traffic on mobile networks is typically downlink traffic[26]. Consequently, the traditional approach of awarding paired spectrum (i.e. a 50/50 split of uplink and downlink spectrum) risks that a large part of the spectrum remains underutilised.

The 700MHz band will be awarded in the UK in a manner that goes against most of the above principles. The majority of the band will be used for a 2×30MHz block of paired spectrum. In addition, the competitive landscape in the UK mobile market and the spectrum caps recently communicated by Ofcom for the upcoming spectrum auctions[27] suggest that it is likely that several operators will gain access to at most 2×10MHz in the band. Such small holdings are unlikely to be 'future-proof' in light of the above-mentioned requirements.

In addition to this, recent auction results from other developed countries provide an indication that the mobile operators' willingness to pay for additional low-frequency spectrum is potentially decreasing (or at least not significantly increasing). Figure 4-2 summarises the prices for recent European 700MHz auctions and compares these to the prices raised in previous 800MHz auctions. It also includes a comparison of the recent US 600MHz auction with the prices raised in the earlier 700MHz auction.

Figure 4-2: Spectrum price benchmark for successive low-frequency spectrum auctions[28, 29]



[25] Vodafone, 'Vodafone Response to Ofcom Call for Input: Spectrum above 6GHz for future mobile communications', February 2015.

[26] International Telecommunication Union, 'Report ITU-R M.2370-0, IMT traffic estimates for the years 2020 to 2030', July 2015.

[27] Ofcom, 'Ofcom sets rules for mobile spectrum auction', July 2017.

[28] All spectrum prices on this chart include one-off auction prices as well as the present value of associated licence fees. All prices are shown as GBP per MHz per unit of population, thereby adjusting for differences between the amount of spectrum awarded and the size of countries. Prices have also been scaled to be equivalent to a licence duration of 20 years.

[29] Comparisons between auctions are inherently difficult, as many different factors contribute to the fees ultimately raised. For example, there were four operators competing in the German 2010 auction for 800MHz, leading to fierce competition as there was not enough spectrum available for

There are a number of good reasons why operators' willingness to pay has decreased when looking at 700MHz relative to 800MHz spectrum:

- 800MHz was the only option to provide high-speed mobile data coverage (using 4G technology) with low-frequency spectrum.
- Today, newer technologies are more focused on higher frequencies. For example, the 3.5GHz band is considered a 'pioneer band' for 5G and discussion on future bands are increasingly focusing on millimetre wave spectrum. This is because higher-frequency bands can provide larger carrier sizes and the smaller antennas required at high frequencies make the introduction of Massive MIMO easier.
- Networks are becoming denser as operators deploy more sites, especially in high-traffic areas. This erodes the reliance on low frequencies, a trend that will be exacerbated once small cells are deployed.
- With the 700MHz band (and other future bands made available), operators are continuously growing their spectrum portfolios. If they continue paying current prices, the implied spectrum costs per unit of revenue increases starkly. Operators simply do not have the financial means to do so in the long term.

Despite the conclusions of the Lamy Report and decisions made at WRC-15, the mobile industry is continuing its lobbying for additional spectrum below 694MHz. In particular, the GSM Association (GSMA) is lobbying for the 600MHz band to be made available globally (including Europe) [30]. This would provide an additional 2×35MHz in a similar configuration to the existing three low-frequency mobile bands. We believe that there is a significant risk that this will result in a sub-optimal solution, reinforcing some of the shortcomings that have been created by the current low-frequency band plans:

- Mobile operators rarely hold more than 2×10MHz in a band, preventing them from maximising the benefits from future technologies such as 5G.
- Symmetric capacity for uplink and downlink traffic is not well suited to today's (and likely future) highly asymmetric capacity requirements.

4.5. Summary of future spectrum demand

Sound arguments can be brought forward by all current spectrum users that they require access to additional capacity within 470-960MHz:

- Broadcasters are seeing an increased demand for higher-definition channels, which may not be offset by improvements in transmission and encoding technologies.
- Mobile data traffic will continue growing, resulting in demand for further capacity. Although there is evidence to suggest that the intrinsic value for incremental low-frequency spectrum may be falling.
- Other mobile-based services, such as GSM-R, will look for additional spectrum resources to transition to the latest technologies.
- For other users, such as IoT/SRDs, significant further growth in the number of wireless devices is expected, which could in turn increase spectrum demand.

Given this wide-ranging and growing demand for low-frequency spectrum, changes in allocations should be made in a way that maximises the benefits across all parties. In particular, changes in allocations should only occur where it is clearly demonstrated that the benefits of doing so exceed the cost of displacing the existing use and where there is no other lower cost solution to meeting the additional demand.

all operators to gain 2×10MHz. By the time of the 2015 700MHz auction, Telefonica had acquired E-Plus. Hence, there were only three players competing for 2×30MHz and the auction cleared relative quickly with all operators acquiring 2×10MHz. However, the emergence of competition did not lead to an equivalent increase in spectrum fees in France, where the number of MNOs increased from three in the 2011 800MHz auction to four in the 2015 700MHz auction.

30 GSMA, '600MHz for mobile broadband', June 2017.

5 Options for more mobile capacity in 694-960MHz

As highlighted in the previous sections, there is growing demand for additional capacity below 960MHz from a range of users. At the same time, all spectrum from 470-960MHz is being utilised at present and there is a requirement from practically all users to (at least) maintain their existing spectrum allocations. Therefore, no straightforward solutions exist to provide additional spectrum / capacity to mobile services or other users.

This issue was highlighted by discussions at WRC-15 on whether to give co-primary allocation to mobile in 470-694MHz. Except for parts of ITU Region 2, the decision was to refrain from doing so, given the impact that such a decision could have on broadcasting services. In addition, it was agreed to only re-visit this issue as part of a wider debate about the use of 470-960MHz at WRC-23.

With 470-694MHz already subject to such intense debate, the focus of this report is to consider the remaining spectrum – i.e. 694-960MHz. Our aim is to consider an approach that moves away from the well-trodden path of making piecemeal decisions about incremental slivers of spectrum. Instead, we consider the possibility of re-shaping significant parts of 690-964MHz in order to make more efficient long-term use of the spectrum and thereby meet the growing capacity demand from various users, including from mobile services. We have termed the potential capacity increases that could result from such an exercise the **'defragmentation dividend'**.

5.1. Options to realise a 'defragmentation dividend'

In this section, we outline three potential band plans that could achieve a 'defragmentation dividend'. When identifying the candidate defragmentation options, we were looking for solutions that:

- dedicate more spectrum to the downlink for both mobile and other mobile-based services such as PPDR and GSM-R (to align with the asymmetry of data traffic)
- create the option for larger carriers (to allow the best use of new technologies such as 5G)
- provide more capacity to mobile-based services to support traffic growth over the coming years.

The options have been chosen to illustrate the general principles that could underlie a 'defragmentation dividend'. Whilst we quote specific frequency ranges for use by different services, this is to provide initial estimates of the capacity benefits that these solutions can provide. We believe that it is too early for detailed proposals, but that the options discussed enable us to identify and assess the general benefits, costs and constraints of a defragmentation from 694-960MHz.

When reconfiguring such a large frequency range, it is inevitable that some services will need to be relocated and inconvenienced. Through the proposed solutions, we have tried to minimise this impact where possible. Using a long-term planning horizon (i.e. 2030 and beyond) is one key factor to minimise transition cost. Another factor is the identification of potential migration arrangements. The second reason to highlight specific frequency ranges is to indicate where we see potential for parts of the existing band plan to remain in place for a certain period of time as users migrate to a defragmented band plan.

We assume that commercial mobile, GSM-R and PPDR services would all be provided within the FDD/TDD/SDL bands identified in the defragmented band plans. At this stage, we do not consider exactly how much spectrum, or which specific frequencies, would be used by each of these services.

We also do not make any assumptions as to whether these mobile-based services are assigned dedicated frequencies and/or use dedicated networks, as opposed to sharing spectrum and/or networks with mobile operators. Even in the UK, where the government has signed an agreement with EE to host the PPDR network on its commercial network, this contract expires in 2032, i.e. towards the beginning of the period we are considering for this study. We thus suggest that future studies are conducted to consider these issues, including how the capacity improvements are shared between mobile, GSM-R and PPDR.

Figure 5-1 summarises the current use of the range 694-960MHz (as per Section 3) and introduces the candidate options identified, which are discussed in the subsections below.

Figure 5-1: Potential defragmentation options

5.1.1 Option 1 – Large FDD band

This first defragmentation option is to create a single large FDD band. This band would allow for large carriers, enabling maximum use of 5G (and other future) technologies. At the same time, the band could be placed such as to minimise the impact on other uses. By offering paired spectrum, using FDD technology, this option relies on proven technologies and thereby minimises the impact on device ecosystems.

The FDD band would be 2×85MHz in size, with the uplink stretching from 736–821MHz and the downlink being from 875-960MHz (i.e. encompassing the whole current 900MHz and GSM-R bands as well as the duplex gap). In addition, 65MHz of spectrum would be available from 696–731MHz (35MHz) and 832–862MHz (30MHz). We assume that this would be used for two SDL bands.

This option would provide of total of 235MHz for mobile/PPDR/GSM-R services, with 150MHz being used for the downlink. Compared to the current situation (which provides 119MHz for mobile downlink[31]), this would provide approximately 25% of extra downlink capacity.

5.1.2 Option 2 – Three TDD bands

This option is more ambitious than the first one. The intention is to create significant extra capacity for mobile and other mobile-based services (such as PPDR and GSM-R), whilst minimising the number of other existing uses that need to be migrated. It involves the creation of three large unpaired mobile bands:

- 120MHz in the range 701–821MHz (i.e. from the bottom of the frequency range to the upper end of the current 800MHz downlink band)
- 30MHz in the range 832–862MHz (i.e. at the current location of 800MHz uplink)
- 85MHz in the range 875–960MHz, stretching across the 900MHz band but also including spectrum currently used for GSM-R as well as the 900MHz duplex gap.

This would provide a total of 235MHz for mobile/PPDR/GSM-R services using Time Division Duplex (TDD) technology. Assuming that approximately 80% is used for the downlink[32], this would create 188MHz for downlink use, nearly 60% extra capacity compared to the current situation.

Critically, this option would have a limited impact on other spectrum users as it would leave PMSE (in the 800MHz centre gap) as well as SRDs and IoT devices (862-875MHz) effectively undisturbed.

Furthermore, there may be a viable migration path for mobile services to further reduce the transition costs associated with this defragmentation option. It would be possible to transition to the proposed band plan in a stepwise fashion, by first creating (and migrating to) the lower two TDD bands, whilst leaving the existing 900MHz band in place. The advantage of leaving one of the existing mobile bands temporarily undisturbed is that it would reduce issues caused by legacy mobile devices, as they can continue to operate in this band (although they could no longer use the 700MHz and 800MHz bands). Consequently, there may be no need for a programme to ensure that all legacy devices are replaced prior to defragmentation. The downside is that the extra downlink capacity is reduced to approximately 30% during the transition. Once the number of legacy devices falls to a manageable level, the full transition could take place – also taking into account the requirements of GSM-R and other services using spectrum in the 900MHz duplex gap.

5.1.3 Option 3 – One TDD band

This third – and most ambitious – option involves re-purposing all spectrum from 710MHz to 960MHz for use by mobile/PPDR/GSM-R services in an unpaired configuration, suitable for use by TDD technology.

We have assumed that that a small (6MHz) guard band will be required at the bottom of the band to minimise the risk of interference with DTT services; and that 10MHz is reserved at the bottom of the band for other uses that require migration from their current frequencies (e.g. SRDs/IoT devices). This still leaves 250MHz of spectrum for mobile/PPDR/GSM-R services. Assuming that approximately 80% of capacity is used for the downlink, this is the equivalent of 200MHz of downlink spectrum. This represents an increase of nearly 70% in downlink capacity relative to today.

This option would require all other existing services (e.g. PMSE, SRDs, IoT) to be migrated from their current spectrum holdings to the 10MHz at the bottom of the band, or indeed to another

[31] The current situation includes downlink spectrum in the 900MHz band (35MHz), 800MHz band (30MHz), 700MHz band (30MHz), 700MHz SDL (assumed to be 20MHz) as well as for GSM-R (4MHz).

[32] International Telecommunication Union, 'Report ITU-R M.2370-0, IMT traffic estimates for the years 2020 to 2030', July 2015.

solution outside of the 694–960MHz range. We consider this to be a significant issue and discuss it in more detail below.

Again, it would be possible to transition to this option in a stepwise fashion by leaving the existing 900MHz band (and possibly the frequency range 862-880MHz) in place temporarily. Once the number of legacy devices falls to a manageable level, the full transition could take place.

5.2. Benefits of defragmentation

We expect that a defragmentation can create significant benefits to users, across at least three dimensions:

- More capacity – There are benefits that would simply accrue from various spectrum users, especially mobile-based services, having more low-frequency capacity available.
- Future-proof spectrum – There are a number of further benefits that could accrue to mobile services as a result of having available spectrum that is better suited to 5G (and subsequent technologies).
- Reduced impact on non-mobile spectrum users – The defragmentation dividend provides an alternative to repurposing more broadcast spectrum below 694MHz to find additional capacity for mobile, on the assumption that this would be the most likely alternative for extra capacity if a defragmentation does not take place.

In this section, we discuss the various facets of these benefits.

5.2.1 Incremental low-frequency capacity for mobile

The primary benefit of defragmenting 694-960MHz would be an increase in the low-frequency capacity provided to mobile, PPDR and GSM-R services, enabling them to meet future traffic growth. Critically, this additional capacity could serve traffic generated in all areas of coverage, including both in rural areas and indoors. Capacity to these locations cannot be provided using higher frequencies without the large cost of deploying a substantial number of additional base station sites. A defragmentation dividend would also enable other mobile-based services, such as PPDR and GSM-R, to transition to suitable future-proof networks and provide the required capacity.

Depending on the defragmentation scenario, the source of the capacity increases may be twofold:

- The proposed options make more spectrum available for mobile-based services – either through elimination of guard bands and/or displacement of other uses.
- All options rely on an increased use of TDD/SDL technology instead of FDD. First, this reduces the need for duplex gaps. Secondly, it provides the option to create asymmetric network capacity to more efficiently meet today's asymmetric traffic demand.

The anticipated increase in capacity varies depending on the defragmentation option implemented, as illustrated in Figure 5-2. Note that the relevant metric is the increase in downlink (DL) capacity, as currently, using FDD, it is the downlink that limits the capacity of mobile networks. We assume that 80% of TDD capacity is dedicated to the downlink. This metric does not include any additional capacity that will be made in any case from technological improvements or from migrations to the latest technologies as a direct result of a defragmentation.

Figure 5-2: Potential capacity gains

Defragmentation option	Mobile/PPDR/ GSM-R spectrum	Increase in DL capacity[33]
Current situation (post 700MHz)	218MHz	-
1 – Large FDD band	235MHz	~25%
2 – Three TDD bands	235MHz	~60%
3 – One TDD band	250MHz	~70%

The mobile downlink capacity provided in Option 1 increases by 25% relative to the current situation. Whilst being a comparatively modest increase in capacity, we believe that this option would still provide a significant improvement over the current band plan. Also, to put the 25% increase in context, this would effectively be akin to adding an FDD band slightly larger than the 700MHz band (i.e. similar to what could be provided by the 600MHz band).

In contrast, both Options 2 and 3 would provide substantial increases in capacity, by at least 60% compared to the current situation. However, these options rely on migration to TDD technologies – we further discuss this in Section 5.3 below.

[33] Calculated as: the downlink capacity in the scenario (assuming 100% of FDD downlink spectrum and SDL spectrum provides downlink capacity and 80% of TDD spectrum provides downlink capacity) divided by the downlink capacity post-700MHz implementation (119MHz, made up of: 900MHz band (35MHz), 800MHz band (30MHz), 700MHz band (30MHz), 700MHz SDL (assumed to be 20MHz), GSM-R (4MHz) minus 1.

5.2.2 Benefits of future-proof spectrum holdings

In addition to the significant increase in mobile capacity that could be realised, we believe that there are a number of other benefits of defragmentation that would accrue to mobile users:

The availability of larger carrier sizes

Carrier sizes for current 4G technology are limited to 20MHz. However, future technologies such as 5G will use larger carriers. Therefore, increasingly larger contiguous blocks of spectrum are required to take full advantage of technological developments.

At present, UK operators are unable to even utilise the maximum carrier sizes for 4G in low frequencies. The 700MHz and 800MHz bands are both just 2×30MHz in size, whilst the 900MHz band is 2×35MHz. Although unusually only two operators have spectrum in the 900MHz band in the UK (compared to three or four operators in most other European countries), none of the UK operators hold a 2×20MHz contiguous block in any of these bands.

Through defragmentation, it will be possible to create much larger FDD or TDD bands. Indeed, Option 3 would provide a single 250MHz band, whilst the lower TDD band in Option 2 would be 120MHz in size and the FDD band in Option 1 would be 2×85MHz in size. This would permit numerous operators to deploy much larger carriers than today.

Cost savings from operating fewer bands

Following the award of the 700MHz band (planned for 2020/2021), most UK operators are likely to have spectrum in two or three low-frequency bands. In addition, the operators already have spectrum in the 1400MHz, 1800MHz, 2.1GHz, 2.6GHz and 3.4GHz-3.8GHz bands. More spectrum in the 2.3GHz and 3.4GHz bands will be made available by Ofcom via auction in the short term, with future auctions in e.g. the 3.6-3.8GHz band being highly likely. UK operators will thus have to manage portfolios including up to 10 different spectrum bands, which adds complexity and cost. For example, additional spectrum bands may increase antenna complexity and associated costs.

As illustrated in our three options, a defragmentation of 694–960MHz would reduce the number of low-frequency mobile bands – e.g. to just one band in Option 3. This would simplify things for operators, leading to cost savings. Although Options 1 and 2 would create three bands, it would not be necessary for operators to have holdings in all three bands.

Defined / earlier switch-off for legacy technologies

Although the 800MHz band is used for 4G services in the UK, and the 700MHz band will be used for either 4G or 5G once deployments begin, we understand that Vodafone and O2 currently use the 900MHz band for legacy 2G and 3G technologies. Such legacy technologies provide significantly lower capacity than the latest 4G technologies, and indeed 5G in the future.

Mobile operators do, over time, re-farm spectrum used by legacy technologies for newer technologies. For example, historically the 900MHz band was used exclusively for 2G technologies, but is now also used for 3G. It is reasonable to expect that by 2030, UK mobile operators will have switched off their 2G and 3G networks and so will be using 900MHz spectrum for newer technologies. That said, by that stage 5G and potentially 6G will be available, and 4G will have become the legacy technology.

In summary, there will always be legacy technologies in use, and any defragmentation transition that forces these technologies to be switched off (due to legacy devices not being compatible with the new band plan) will result in an increase in the capacity provided by mobile networks. This benefit is incremental to the capacity increases shown in Figure 5-2 above, which only includes capacity benefits from increases in spectrum for the downlink. That said, given that mobile operators re-farm spectrum to the latest technologies on an on-going basis, this benefit is likely to be modest compared with the benefits from simply having more downlink spectrum available.

5.2.3 Minimised impact on other services

The UHF band is an important asset for the broadcasting and PMSE sectors. This has been recognised in the UHF Decision which also highlighted the relevance of providing long-term support to the EU creative industry[8]. As mentioned, there has been a trend in recent years to repurpose spectrum in a stepwise fashion from broadcasting to mobile in order to meet additional mobile demand. First, the 800MHz band was repurposed, and now a similar process is occurring for the 700MHz band. As discussed above, at 2×30MHz both bands are smaller than is ideal for 5G.

With mobile traffic continuing to grow, there could be a scenario where, after 2030, further repurposing of UHF spectrum from broadcasting to mobile is considered and another spectrum 'slice' could be identified – the 600MHz band mentioned above. The loss of an extra 80MHz from broadcasting/PMSE (the approximate quantity required to create the 600MHz band) would equate to more than a third of the remaining broadcasting/PMSE spectrum. Such a loss of spectrum would inevitably come with very significant costs and, at worst, may even call into question the viability of the DTT platform.

This scenario was considered in our 2014 report for Abertis, Arqiva, BBC, BNE, EBU and TDF entitled 'Future use of the 470–694MHz band', where we estimated the costs associated with ceasing DTT transmissions and migrating consumers to alternative platforms to be EUR38.5 billion across the EU, of which nearly **EUR8 billion** would accrue in the UK. The estimate was derived from examining the impact on consumers (additional equipment costs), operators (cost of enhancing other platforms) and markets (loss of competition) over a 15-year period[34]. The 'defragmentation dividend' provides an alternative to repurposing additional broadcasting spectrum. Whilst the current study considers a different time period – i.e. a defragmentation from circa 2030, the nature of the above costs is unlikely to have substantially changed.

5.3. Constraints and costs of defragmentation

In this section, we discuss various potential constraints of defragmentation.

5.3.1 Transitional licencing and competition issues

The transition to a defragmented band plan could be complicated if it were to occur partway through mobile operators' licences for 700MHz, 800MHz and 900MHz spectrum. Given the current UK licence regime, Ofcom would have limited powers available to change the licence conditions for spectrum bands that have been awarded less than 20 years prior to a de-fragmentation. In other situations, it would have to provide 5 years' notice to the licence holders. This implies that it would be most straightforward to de-fragment the 900MHz band (which unfortunately is best suited for any transitional arrangements). For the 800MHz band, de-fragmentation would be possible around 2033 at the earliest (assuming sufficient notice is given to existing licence holders), whereas the situation is unclear for the 700MHz band as this band is yet to be awarded.

Alternatively, Ofcom could agree to compensate licence holders in exchange for early termination of their licences. Most obviously, compensation would be in the form of licences in the new defragmented band plan. Such a process would likely have numerous detailed issues to overcome – such as:

- Should licensees receive the same quantity of spectrum in the new band plan as the old?
- Should this be the case across all three bands even though some may be more valuable than others?
- Where in the new band plan should licensees be located?
- Should licensees gain contiguous spectrum in the band plan? What if this is not possible?

Having provided existing licensees with appropriate holdings in the new defragmented band plan, Ofcom could then auction any new mobile spectrum created from the defragmentation. Existing licensees would then have the option of supplementing their existing holdings, potentially opening up the option of deploying more advanced technologies across their new and existing holdings.

Although these are important and complex issues, experience of past mobile spectrum release processes indicates they can be resolved. Therefore, they should not be seen as unsurmountable barriers to a defragmentation, and certainly should not prevent more detailed consideration of defragmentation options.

5.3.2 Technical constraints and costs

This section summarises possible technical challenges, and shows that there are no unsurmountable constraints to defragmentation. A more detailed discussion is provided in Annex C.

Use of low frequencies for TDD

Considering the use of TDD in lower bands is not a novel concept. Although not used at present, LTE Band 44 (703–803MHz) is for a TDD arrangement. Serious consideration was given in the US as to whether the 600MHz band should be TDD, with some carriers such as Sprint initially arguing in favour of this. With a band plan separating TDD from other uses, and with the experience that will have been gained in TDD over the coming years, we see no reason why TDD cannot be used extensively in 694–960MHz.

TDD requires coordination between operators (same timing, same uplink/downlink split), otherwise there can be significant interference from one base station working in transmit mode into another working in receive mode on an adjacent channel. This coordination already occurs in higher-frequency TDD bands. If necessary, (frequency) guard bands between different holdings could help alleviate any interference.

TDD works less well when cell sizes are large. A longer range causes increased propagation delay which can result in interference occurring around the time between using downlink and uplink. If operators choose to use these frequencies for extended range cells, then a larger guard-band (in time) might be needed between downlink and uplink transmissions, reducing the capacity provided by the network. Simple calculations suggest that this might only reduce efficiency by about 2%.

We also expect that the achieved cell range will be the same for TDD and FDD, since the same power levels will be used for base station and mobile device transmit as with FDD. We do not anticipate any significant latency penalties from TDD operation – frame sizes can be adjusted as needed.

[34] The modelling period considered was 2015-2029.

Availability of devices

Recent phones (e.g. iPhone 8, Samsung Galaxy) already cover the 700MHz (Band 28), 800MHz (Band 20) and 900MHz (Band 8) bands – a clear indication that devices can tune across this range. At present, this is for FDD use rather than TDD, but TDD is likely to be simpler because there is no need for duplexers in the RF chain.

New devices would need to be able to operate across both the old and the new band plan and to change automatically to the new band plan at the point of switch-over. The devices would typically be introduced a few years before the transition as part of the natural replacement cycle to ensure a widespread base of devices by the transition date. This would require the cooperation of handset manufacturers, which is unlikely to be problematic. While accommodating both old and new plans is not ideal, it might be that by this time much of the RF can be reconfigured using Software Defined Radio (SDR) principles or similar.

In the base station, it is possible that different RF chains might be needed, but this is business as usual for mobile operators who already have many different RF chains and will be adding more bands as they become available (above and below 694-960MHz).

Interference issues with existing uses

Whenever two different services sit alongside each other, there is always a risk of interference. For any defragmentation, detailed studies would be needed to reduce this risk. Such studies often require many man-months of effort, consultation and modelling and we only provide initial high-level observations here.

The main boundary for all options is at the lower edge between mobile and DTT. Although we are yet to see the extent of interference between the 700MHz uplink and DTT, many studies were conducted before settling on the current guard band. Further, interference between the 800MHz downlink and DTT was lower than anticipated by similar studies. Hence, we do not expect any major problems – but if any concerns were identified, additional spectrum could be sacrificed at the bottom of a defragmented band.

There are also boundaries with SRDs. Broadly, these are devices that work in unlicensed spectrum and tend to accommodate interference. They already operate adjacent to mobile systems with various uplink / downlink combinations. It seems unlikely that the new band plan would materially change the interference.

Another boundary may occur at the bottom of the band between mobile and services migrated from their current frequencies. One of the worst cases could be that (migrated) railways relied on FDD, and a cellular TDD system was placed adjacent to it. This may create concerns around handset transmissions interfering with the railway downlink, which would need careful study. Possible solutions might include guard-bands on base stations near to railway systems.

If defragmentation were to occur throughout Europe, cross-country interference would also need to be considered. At a high level, there may be cross-border interference issues with regions that continue to use the old band plan and there could also be issues between countries using the same plan but with unsynchronised TDD transmissions. These situations are likely to require cross-border coordination, but there is ample precedent for such arrangements to be made (e.g. GSM preference channels).

In summary, much work would be needed (but this would also apply in case other frequency ranges would be identified for use by mobile services) but most of these studies have already been undertaken for similar cases and have not resulted in any show-stopping concerns.

Network costs of migration to a defragmented band plan

We anticipate the costs to the operators of migration to be low. It is unlikely that new base station sites will be needed. Existing towers can be used, and antennas either reused or replaced on a one-for-one basis. Base station equipment will need to be upgraded, but this is likely to be needed as part of standard equipment refresh in any case and, given a long enough lead time, can be planned into maintenance cycles.

5.3.3 Economies of scale in devices

Mobile device manufacturers typically design and produce devices either for the global market or large regional markets (i.e. of at least several hundred million inhabitants). For example, Apple produces only three models of the iPhone 8 for the entire global market. If the UK was to adopt a defragmented low-frequency band plan, it is important that device manufacturers include it in their devices with negligible increases in device costs. In this case, we believe that there would be clear benefits from a cross-European approach to defragmentation, for three reasons:

- Assuming that the UK and EU as a whole adopt a defragmented band plan, the resulting market is sufficiently large for mainstream manufacturers to produce tailored models.
- Devices are becoming increasingly agile in terms of the spectrum bands they use. The iPhone 8 supports up to 27 different LTE bands such that one model can support numerous regions with different LTE band plans. Consequently, it is likely that a European defragmented band plan would be catered for by devices aimed at the global market.

- Other regions of the world face the same issue of fragmented low-frequency mobile bands. Therefore, they may well also adopt the same defragmented band plan as Europe.

Overall, we expect that as long as a sufficiently large market (e.g. UK + EU) adopts a defragmented band plan, it is unlikely that device availability would present a constraint or that devices would become materially more expensive due to loss of economies of scale.

5.3.4 Potential migration costs

With changes in spectrum band plans, it is likely that migration costs will also occur. In this section, we discuss the key users that may be affected by such a migration.

We acknowledge that the issue of migrating uses is a highly complex matter. However, with sufficient notice, migrations of the scale required for defragmentation are possible. For example, the DTT community is currently going through significant disruption in order to clear the 700MHz band, which represents approximately 30% of the spectrum currently available to DTT. This programme will take several years of network re-planning, engineering works, consumer communications and in-home support. However, it should ultimately achieve the goal of more efficient use of spectrum.

Also, it may be possible to compensate users for the disruption and costs of migration – either in the form of gaining more spectrum post-defragmentation or through financial compensation (perhaps funded from the proceeds from awarding the newly created bands).

Mobile services

In all options, the existing 700MHz, 800MHz and 900MHz bands would ultimately cease to be used, though some transitional arrangements may see temporary use of the 900MHz band. Although existing devices also use higher-frequency bands, users with outdated devices would experience a substantial reduction in coverage – especially in rural areas and indoors. This would be unacceptable, meaning that prior operators would need to upgrade all consumers upgraded to compatible devices prior to defragmentation. To minimise this issue, it is critical that a defragmented band plan is agreed and standardised as soon as possible, such that devices are introduced several years before the transition and the number of compatible devices in the market at the time of transition is maximised. However, almost irrespective of how early compatible devices are introduced, some users will still have legacy devices at the time of transition. In particular, some M2M devices have long replacement cycles (e.g. smart meters). Operators would need to identify these users and devise strategies to update their devices (e.g. through device replacement subsidies).

Similar activities have been conducted elsewhere. For example, Australian operator Telstra switched off its 2G network in December 2016. Following switch-off, all legacy 2G-only devices no longer worked. In preparation, Telstra ceased selling 2G devices four years prior to switch-off, and publicly announced the switch-off date two years in advance, such that Mobile Virtual Network Operators (MVNOs) using its network could also prepare. It carried out an extensive marketing campaign to inform customers with 2G devices that they needed to upgrade. At the point of announcing the switch-off, Telstra stated that 1% of its traffic was carried by its 2G network. [35]

Given that we do not expect that a defragmentation would be initiated significantly before 2030, it is plausible that compatible devices could be launched several years in advance, and the sale of incompatible devices could be ceased prior to switch off. This should significantly reduce any device concerns. In defragmentation scenarios where at least one of the existing low-frequency bands remains temporarily in use, customers will continue to have access to low-frequency spectrum regardless of whether they upgrade their device. In such circumstances, replacing all incompatible devices is not necessary, reducing migration costs to close to zero.

PPDR

Given the plans of the UK government to host PPDR services on commercial networks, the same concerns regarding legacy devices as for mobile services apply.

GSM-R

GSM-R has only been recently deployed in the UK. There is no clear timetable for a migration towards an LTE-based solution yet, with a potential target date set for 2023. In case the defragmentation concept gains traction, it would be important to time any migration towards the de-fragmented frequencies such that there would be no material incremental costs – we believe this to be possible with sufficient notice provided.

Migration of PMSE, SRDs and IoT

Certain defragmentation scenarios – especially Option 3 – may require the migration of PMSE, SRDs, IoT devices. A broad variety of PMSE devices and SRDs operate in 823–832MHz and 863–870MHz (although arguably the number of PMSE devices

[35] Telstra, 'Its-time-to-say-goodbye-old-friend', 2014, available at: https://exchange.telstra.com.au/2014/07/23/its-time-to-say-goodbye-old-friend/.

that would be impacted by spectrum allocation decisions would be greater should further broadcasting spectrum be repurposed for mobile instead of defragmenting the 694–960MHz range). As these devices access spectrum on a lightly-licensed/unlicensed basis, it is difficult to accurately assess the number of devices in use today.

Unlike mobile phones, many IoT devices are characterised by low unit costs and long lifespans (potentially longer than 10 years). Wireless chips are likely to be embedded and single-band, limiting the potential for future-proofing. Hence, complete device replacement will often be necessary. Additionally, a period of several years' concurrent operation of both existing and new frequencies will be required.

Clearly, such a migration is challenging, especially when the number, location and identity of devices are unknown. However, similar (but smaller scale) migrations have been conducted in the past. As part of the process to clear the 800MHz band, Ofcom successfully migrated wireless microphones from Channel 69 (854–862MHz) to Channel 38 (606–614MHz). It undertook an extensive communication programme to alert users of the need to replace their devices. In total, GBP44.67 million was spent replacing devices. [36]

Given that the number and nature of PMSE, SRDs and IoT devices in operation in the 694–960MHz range in 2030 is very difficult to predict, there are clear challenges to estimating the cost of migration. However, in light of the number of devices that are already in operation, the costs could possibly be an order of magnitude higher than the above-stated costs previously incurred for migrating PMSE. Depending on the defragmentation option considered, further studies looking at the cost of migrating SRDs may be required.

5.3.5 Summary of constraints

In summary, we have not identified any technical, regulatory or commercial issues that would absolutely prevent a defragmentation in 694–960MHz. If sufficient notice was provided, many of the potential migration costs are greatly reduced or eliminated. That said, there are two main areas of substantial cost, namely the cost to replace mobile devices that are not upgraded as part of the natural device replacement lifecycle and the cost of migrating PMSE, SRDs and IoT devices to new frequencies. A summary of how the potential constraints apply to the three proposed defragmentation options is shown in Figure 5-3.

Figure 5-3: Summary of key constraints

	1-Large FDD band	2 - Three TDD bands	3 - One TDD band
Transitional licencing?	o	o	o
Technical constraints?	+	o	o
Migration costs	–	o / –	– – –

All of the proposed options will require transitional licencing as they include changes to the current band plans (and associated spectrum licences awarded by Ofcom). Whilst we do not believe that a technical implementation of TDD will pose a significant issue below 1GHz, Option 1 is the only solution that relies on using the established FDD ecosystem. Finally, we expect that migration costs for Option 3 will be significantly higher than for the other two options, as it will require migration of the licence-exempt uses from 863-876MHz. For Option 2, the ability to leave the 900MHz intact for a period of time for transitional purposes could reduce migration costs significantly.

[36] Ofcom, 'Clearing the 800MHz band', 5 August 2010, available at https://www.ofcom.org.uk/__data/assets/pdf_file/0021/46551/statement.pdf.

6 Conclusions

In June 2017, at the European Spectrum Management Conference in Brussels, a debate was initiated regarding the long-term future of the 470-960MHz range, to question whether the existing allocations were fit for purpose over the long term. With an extensive debate already ongoing about the use of 470-694MHz, the objective of this report is to contribute to the wider debate by specifically considering the 694-960MHz range.

We believe that now is the ideal time to launch such a discussion. The recommendations of the Lamy Report locked in the current allocations until 2030. This opens up the opportunity to take a more holistic approach that considers the full 470-960MHz range in order to maximise it use over the long term. Further, reconfiguration may take many years to complete; therefore, consideration of the optimal solution needs to occur now such that decisions can be made that provide sufficient implementation time ahead of 2030.

Within the report, we have considered the option of creating a **'defragmentation dividend'** by reconfiguring the existing band plans between 694-960MHz to make additional capacity available to mobile services and other spectrum users. Our analysis identifies large potential benefits from defragmentation. Depending on the exact solution chosen, it could provide up to 70% additional downlink capacity for mobile-based services. Even in the most pessimistic case, we expect there to be scope for an increase in downlink capacity of 25%, which is not dissimilar to the capacity that would result from the creation of a 600MHz band. In addition to offering more long-term capacity, a defragmented band plan would also enable mobile operators to have larger contiguous blocks of spectrum, better positioning them to exploit 5G (and other future) technologies. Finally, defragmentation would avoid the alternative of repurposing additional spectrum below 694MHz and thereby maintain the DTT platform and PMSE use in the long term.

Naturally, carrying out a defragmentation would be a complex task, but our analysis of technical, regulatory and commercial constraints has not identified any unsurmountable issues. That said, a number of obstacles should be addressed ahead of any defragmentation. Notably, the UK is not a sufficiently large market to adopt a new mobile band plan in isolation. Therefore, the case for defragmentation is contingent on a substantial market (e.g. the EU) adopting it. Whilst our analysis of existing and future use was focused on the UK, we expect that the EU (and potentially other markets) would see similar benefits to defragmentation given the similarity of current spectrum assignments. Another notable obstacle is that legacy mobile devices and other existing uses may need to be migrated to new frequencies. However, provided that sufficient notice is given, the cost of such migrations can be minimised.

To explore the range of defragmentation options, we have identified three different candidate band plans. Further study will be required to identify an optimal solution, which may vary from our proposals. However, our analysis has highlighted key principles that we would expect to guide any defragmentation:

- The capacity benefits are largest when the defragmented band plan is (largely) used for TDD, due to the asymmetric capacity this provides.
- The costs for mobile services reduce with a staged implementation (e.g. where one of the existing bands is left undisturbed for a period of time), as the number of legacy mobile devices declines over time.
- Any solution that requires the migration of SRDs/IoT devices in the 863–870MHz range substantially increases the cost of implementation for other, non-mobile, spectrum users.

In conclusion, we believe that a 'defragmentation dividend' offers an interesting and credible long-term solution to increase capacity for mobile-based services in the UK. Therefore, we recommend that further study is conducted to fully explore the defragmentation options available as well as the merits of each proposed solution.

Given that the case for defragmentation in the UK is contingent on the EU (or another substantial market) also opting for a defragmentation, we recommend that UK policy makers engage with their European/international counterparts to ensure that defragmentation is further evaluated and given appropriate consideration in fora that discuss the future of 470-960MHz. Notably, we recommend that UK policy makers:

- Raise the concept of defragmentation within the RSPG and with the European Commission and recommend that EU-wide assessments are conducted.
- Influence CEPT's position ahead of WRC-19, such that the future use of 694-960MHz (including a potential defragmentation) factors into discussions at WRC-23, rather than the focus solely being on 490-694MHz).

Annex A About the authors

On behalf of Digital UK, Aetha Consulting and Webb Search – and specifically Lee Sanders, Marc Eschenburg and William Webb – have written this paper to consider the case for a 'defragmentation dividend' in the UK.

Aetha Consulting

Aetha Consulting helps players in the telecoms industry to develop creative and sustainable solutions to the challenges facing them in a constantly changing environment. We specialise in undertaking rigorous assessments to support major strategic and regulatory decisions.

Throughout the recent unprecedented growth of wireless services, we have been at the forefront of spectrum policy. Our consultants have assisted regulators to award spectrum and develop regulatory frameworks, including supporting the European Commission to tackle issues such as spectrum trading and the digital dividend. We also support operators to understand their spectrum needs, value spectrum and bid in auctions. We have supported bidders in over 40 spectrum awards worldwide in just the last 5 years.

Lee Sanders (Partner) has been at the forefront of spectrum developments across the world for more than 15 years. He has led several high-profile spectrum studies for regulators such as the European Commission, Ofcom (UK) and the IDA (Singapore). He has also led numerous projects to advise operators on spectrum issues, in particular to develop spectrum strategies and to value spectrum. Lee authored Aetha's previous study in 2014 on behalf of a consortium from the broadcasting industry entitled 'Future use of the 470–694MHz band'.

Marc Eschenburg (Partner) has worked in the telecoms industry since 2008 advising operators as well as regulators and other government bodies on a wide range of issues. He has been very active in the area of radio spectrum policy, advising regulators such the BIPT (Belgium), Ofcom (UK) and ANRT (Morocco) on spectrum issues. He has also advised more than 20 operators worldwide to develop valuation models and prepare for auctions.

Webb Search

Webb Search provides technical and strategic consultancy across the wireless communications space, advising CEOs, Government Ministers and regulatory bodies.

William Webb has decades of experience of wireless/mobile technologies. William was the Head of Research and Development and one of the senior spectrum strategists at Ofcom, the UK regulator. In this role he led a number of key policy initiatives including the Spectrum Framework Review, which set long term Ofcom strategy in all areas of spectrum management. Other key policy roles included taking the lead on ultra-wideband, the licence-exempt framework review, spectrum usage rights and most recently cognitive or white space access to the spectrum.

Annex B FDD and TDD technologies

This annex explains in a non-technical manner how frequency division duplex (FDD) and time division duplex (TDD) technologies work as well as how they differ.

Cellular communications is two-way – the network sends signals to the device (the 'downlink') and the device sends signals back to the network (the 'uplink'). This is called 'duplex' transmission and differs from broadcasting where the transmission is one way ('simplex' transmission). There are two main ways to arrange for duplex transmission:

- The network and device can transmit at the same time, but on different frequencies so that they do not interfere with each other. This is called frequency division duplex (FDD).
- They can transmit at different times but on the same frequency, this is called time division duplex (TDD).

There are advantages and disadvantages to each. FDD is simple to implement and is well-understood, being widely used in all generations of cellular communications (although TDD has been the preferred method for home cordless phones, Wi-Fi routers and more for decades). TDD brings a key advantage that the proportion of the capacity available to the downlink and the uplink can be varied, dynamically if needed, to accommodate traffic such as video streaming where 90% or more can be downlink. This is achieved by varying the proportion of the time used for downlink transmission compared to uplink transmission. However, because one base station might be transmitting on the TDD channel while a nearby one, perhaps owned by a different operator, might be receiving, the risk of interference is higher. For this reason, TDD networks are often synchronised so that they all have simultaneous use of downlink and uplink, which adds complexity.

The choice of FDD or TDD needs to be reflected in the spectrum assignment. FDD requires 'paired' spectrum – a downlink and an uplink typically separated by tens of MHz (the 'duplex gap'). TDD is simpler as paired spectrum is not required.

It can be seen from this that TDD is likely to make more efficient use of spectrum, since it avoids wasting uplink spectrum when the traffic is predominantly downlink and avoids the need for duplex gaps (and any associated additional guard bands). However, TDD is more complex, requiring coordination between operators

Annex C Technical constraints and costs

This annex discusses the technical constraints raised in Section 5.3.2 in more detail. It sets out possible technical challenges and concerns, and shows that there are few practical difficulties to implementing the defragmentation options proposed.

Use of low frequencies for TDD

Mobile networks have been using frequencies in and around 694–960MHz for several decades, so there cannot be any doubt that these frequencies can be used for mobile-like services. As discussed, all low-frequency mobile bands are currently configured for FDD (including GSM-R). However, recent trends have been for new mobile bands to be configured for TDD. This is because:

- Data traffic now predominates and is generally biased heavily towards the downlink with the result that in an FDD arrangement the uplink is underutilised. [37],
- MIMO antennas are increasingly being used to improve spectrum efficiency and TDD allows for the channel estimates derived on the uplink to be reused on the downlink, reducing the need for training sequences and improving overall performance.
- Voice can be carried using Voice over LTE (VoLTE) and so separate voice-oriented channels are no longer so important.

As a result, two of our three options assume some element of TDD. This is important as the migration to TDD provides the majority of the capacity gains.

TDD requires coordination between operators such that they use the same timing and the same uplink/downlink split[38]. Otherwise, there can be significant interference from one base station working in transmit mode into another working in receive mode on an adjacent channel. This need for coordination already occurs in other bands where it is successfully achieved, so there should be little problem in enabling it for lower frequencies. If problematic, then guard bands (in frequency) between different holdings can help alleviate any interference.

TDD works less well when cell sizes are large. A longer range causes increased propagation delay which can result in interference occurring around the time between using downlink and uplink. If operators choose to use these frequencies for extended range cells, then a larger guard-band (in time) might be needed between downlink and uplink transmissions, reducing the capacity provided by the network. Simple calculations suggest that this might only reduce efficiency by about 2%[39]. This can be determined on a network-by-network and region-by-region basis and does not need to be part of the band plan.

We also expect that the achieved cell range will be the same for TDD and FDD, since the same power levels will be used for both base station and mobile device transmit as with FDD. In particular, despite the uplink only being used for some fraction of the time, the transmitted power is the same as with FDD and so the range will be unchanged, all other factors being equal. We do not anticipate any significant latency penalties from TDD operation – frame sizes can be adjusted as needed[40].

There has previously been consideration of TDD in the 694–960MHz range or similar. LTE Band 44 (703–803MHz) is for a

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[37] Due to lower modulation classes being used on the uplink compared to the downlink (caused by the weaker link budget), the downlinks of FDD networks sometimes provide greater capacity than the uplink. However, the weaker link budget is sometimes balanced by more sensitive receivers at the base station than in the handset.

[38] The exact downlink/uplink split is unknown at present, but could possibly remain at 80/20, based on today's usage.

[39] The key problem occurs for base-station to base-station interference. This is because mobile devices can be instructed to modify their timing advance to accommodate delays, but this is not possible at the base station. Transmissions from one base station can be "in flight" to another as it starts uplink reception, interfering with the signal from mobiles. For a rural network with a (very large) 25km cell radius, the propagation time from one cell to another would be around 0.16ms. For a typical frame size of 10ms this comprises 1.6% of the resource. However, in areas where such large cells are used, capacity is rarely problematic. In urban areas where cell sizes are around 1/10th of this level, then the penalty is trivial. Also, approaches such as scheduling the mobile closest to the base station to transmit first can ensure that any interference has the least effect.

[40] Note that some claim that the range of TDD is less than FDD because devices only transmit (say) half the time and hence achieving the same data rates requires higher transmit powers enabling higher level modulation. This is true if TDD is implemented in the same band plan as FDD. However, that is not what we propose here. For example, instead of a 2x10MHz FDD pair, a single 1x20MHz TDD channel would be allocated. A terminal accessing this channel for 50% of the time would achieve the same throughput at the same power level as one accessing a channel of

TDD arrangement, although it does not appear to be used at present. Serious consideration was given in the US as to whether the 600MHz band should be TDD, with some carriers such as Sprint initially arguing in favour of this arrangement. However, ultimately the decision was made to adopt an FDD band plan primarily because adding TDD into an FDD band can be inefficient due to interference between the two formats. The greatest benefits are achieved if the whole band, or substantial proportions of the band, can be used for TDD. There has also been some hesitancy to use TDD in the highly valuable UHF until it is better proven in other bands – critically, this is happening now.

In summary, with a defragmented band design clearly separating TDD from other uses, and with the experience that will have been gained in TDD over the coming years, we see no reason why TDD cannot be used extensively in the 694–960MHz range.

Availability of equipment that tunes across the whole 694–960MHz range

We will first consider the availability of user devices. As an example, the iPhone 8 supports LTE in Bands 1, 2, 3, 4, 5, 7, 8, 11, 12, 13, 17, 18, 19, 20, 25, 26, 28, 29, 30 and 66 (plus TD-LTE in Bands 34, 38, 39, 40, and 41). This means it covers 700MHz (Band 28), 800MHz (Band 20) and 900MHz (Band 8) – a clear indication that devices can tune across this range. At present, this is for FDD use rather than TDD, but TDD is likely to be simpler because there is no need for duplexers in the RF chain. It is also generally achieved with a number of switchable RF front-ends rather than one single RF chain that can accommodate the entire band – this works well but does add some device cost and complexity. Over time, it is highly probable that chipsets and antennas will improve such that tuning across the whole band becomes increasingly economic and standard.

In the base station, it is possible that different RF chains might be needed, but this is business as usual for mobile operators who already have many different RF chains and will be adding more bands as they become available (e.g. 3.4GHz). It would seem very likely that base station antennas able to operate from 700-960MHz would be available – for example, a paper in the International Journal of Antennas and Propagation[41] describes a dual-polarized base station antenna supporting 698MHz to 960MHz, covering all current mainstream low-frequency bands.

Device issues

New devices would need to be able to operate across both the old and the new band plan and to change automatically to the new band plan at the point of switch-over. The devices would typically be introduced a few years before the transition as part of the natural replacement cycle to ensure a widespread base of devices by the transition date. This would require the cooperation of handset manufacturers, which is unlikely to prove problematic. While accommodating both old and new plans is not ideal, it might be that by this time much of the RF can be reconfigured using Software Defined Radio (SDR) principles or similar. The only additional component might be a duplexer, rendered obsolete by the transition to TDD. Once the transition has completed, support for the old band plan can be dropped from future devices.

Interference issues with existing uses and the need for guard bands

Whenever two different services sit alongside each other, there is always a concern about interference. For any potential band plan, there would need to be a detailed study to determine potential interference issues. These studies often require many man-months of effort, consultation and modelling. We make no attempt to undertake such a study here, but instead provide some high-level comments about where the most problematic interference issues might reside.

The main boundary for all options is at the lower edge between mobile and DTT. In Option 1, there is possibly a very small guard band (2MHz) and SDL is used in those frequencies rather than the 700MHz FDD uplink that will be used in the coming years. Although we are yet to see the extent of interference between the 700MHz uplink and DTT, many studies were conducted before settling on the current guard band. Further, interference between the 800MHz downlink and DTT was lower than anticipated by similar studies. Hence, we do not expect any major problems – but if any concerns were identified, a 5MHz block could be sacrificed at the bottom of the band to re-instate a 7MHz guard band. For Options 2 & 3, there are larger guard bands in place, which should further reduce interference concerns.

There are also boundaries with SRDs. Broadly, these are devices that work in unlicensed spectrum and tend to accommodate interference. They already operate with mobile systems in nearby bands with various combinations of uplink and downlink. It seems unlikely that the new band plan would materially change the

half the bandwidth for all of the time. (Indeed, it would also likely use less battery power as it could then sleep for the remainder of the time.) Hence, these criticisms of TDD do not apply to our proposal.

41 Samb, Wu, Liu and Jie, 'Development of Ultra-Broadband Base Station Antenna for All Mainstream LTE 700/800/900 MHz Frequency Bands', November 2014, available at: https://www.hindawi.com/journals/ijap/2014/201914/.

interference. However, there are many different SRDs, and new IoT-related networks are currently being introduced. Therefore, a study across each SRD/IoT solution would be needed. If there were issues, it might be possible to determine these well in advance of the re-plan and new SRDs might have enhanced filtering, or similar, to accommodate. Hence, we do not expect major issues, but we do anticipate that multiple studies and discussions with many diverse stakeholders will be needed.

Another boundary may occur at the bottom of the band between mobile and services migrated from their current frequencies. Under some scenarios, it is possible that the interference environment to the railway bands might change. We would anticipate that the railways will have migrated from GSM by this time, perhaps to an LTE-based or 5G-based solution. The solution they adopt might be influenced by the future band plan. If it transpired that the railways had an FDD solution, and a cellular TDD system was placed adjacent to it, there might be concerns around handset transmissions causing interference to the railway downlink, which would need careful study. Possible solutions might include guard-bands on base stations near to railway systems.

If a wider adoption of a defragmented band plan at European level is considered (which we believe to be important for economies of scale to be realised), cross-country interference would also need to be considered. At a high level, there may be cross-border interference issues at the borders with other regions that continue to use the old band plan (e.g. Eastern Europe) and there could also be issues between countries using the same plan but with unsynchronised TDD transmissions. These situations are likely to require renewed cross-border coordination, but we note that there is ample precedent for such arrangements to be made – for example, in the context of GSM preference channels.

In summary, much work would be needed (but this would also apply in case other frequency ranges would be identified for use by mobile services) but most of these studies have already been undertaken for similar cases and have not resulted in any show-stopping concerns.

Network costs of migration to a defragmented band plan

We anticipate the costs to the operators of migration to be low. It is unlikely that new base station sites will be needed. Existing towers can be used, and antennas either reused or replaced on a one-for-one basis. Base station equipment will need to be upgraded, but this is likely to be needed as part of standard equipment refresh in any case and, given a long enough lead time, can be planned into maintenance cycles.