Foreword

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Low band UHF spectrum, in particular frequencies sub-one gigahertz, has become a highly valued asset – sought after and used by a wide range of services, including digital terrestrial television (DTT), Programme-making and special events (PMSE) and mobile services among others.

Given the critical importance of low-frequency UHF spectrum for a variety of sources and the relevance of this subject to WRC-23, the UK Spectrum Policy Forum considered it appropriate to explore the long-term use – post 2030 – of 470-694 MHz prior to WRC-2023 and subsequent regulatory implications from a UK perspective.

Earlier this year, the UK Spectrum Policy Forum commissioned an independent report to Coleago Consulting to add to the evidence base and present a suite of options for policy and regulatory makers.

The report considers the current use of these frequencies, market, and technology developments, as well as potential changes in viewing and consumer habits, and proposes four potential regulatory scenarios for the future of 470-694 MHz frequencies. The four scenarios are as follows:

- Scenario 1 'Status Quo'
- Scenario 2 'Flexible Use'
- Scenario 3 'IMT600 band plan'
- Scenario 4 'Transition to IPTV'

UHF spectrum will remain a scarce valuable resource and, according to the Coleago report, it may not be possible to fully accommodate all stakeholder groups simultaneously. As a result, and understandably, there are competing views as to how the UK can best use these frequencies and the impact on spectrum users.

The UK Spectrum Policy Forum does not advocate nor recommend any of the four potential future scenarios detailed in the report. Similarly, no single scenario is considered more likely than any of the others in the report. Further commercial and technical studies will be necessary to make an informed decision on the various options detailed.

Moreover, there is a significant degree of uncertainty about future trends, upcoming developments and other external factors that might have an impact in each of the four scenarios, as these are based on future-looking forecasts of likely spectrum demand.

With changes in DTT use, ongoing technological developments in mobile, DTT and PMSE systems and with future spectrum requirements yet to be identified, decisions on changes to spectrum allocation's will require careful consideration.

Future Utilisation of the 470-694 MHz Band in the UK

FINAL REPORT

prepared for

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coleagoconsulting

Content

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1. Executive Summary

Spectrum is a vital national resource for the United Kingdom which generates significant economic and social benefits for citizens and consumers. Spectrum needs change over time in response to technology and market developments, so it is incumbent on spectrum management authorities to periodically review whether the current spectrum allocations are optimal.

The ITU WRC-23 Agenda Item 1.5 will consider future uses of 470-694 MHz band in Region 1, given that the main existing use, broadcasting, faces potentially far-reaching market and technological changes over the coming decade. As a result, it is appropriate for the UK to consider the future needs for the spectrum from existing uses – principally DTT, and PMSE use in the interleaved spectrum – and potential other uses such as mobile communications for which the spectrum is attractive in view of its favourable propagation characteristics. It is in this context that the UK Spectrum Policy Forum have commissioned this report which identifies and analyses possible future scenarios for use of the 470-694 MHz band in the UK in a post-2030-time frame.

We believe the key trends that will drive changes in UHF spectrum use are:

- the decline of linear TV and growth of alternative platforms for linear and non-linear television;
- the increasing demand for mobile spectrum and the particular importance of low band in maximising both economic and social benefits from 5G and beyond;
- the continued growth in the use of PMSE equipment such as wireless microphones, in-ear monitors and production services for radio and TV to support broadcasting, news gathering, streaming services, theatrical productions and special events, such as concerts, sport events, conferences and trade fairs; and
- the convergence between mobile and broadcasting.

After conducting an extensive literature search as well as holding interviews with 17 stakeholder organisations and considering the above trends, we have identified four main scenarios as follows:

- Scenario 1, “Status Quo” – no change in allocation. In this scenario mobile broadband demand continues to grow at a similar level to recent years, but IoT growth is slower than expected. MNO revenue growth is set back due to the uncertain economic outlook and the MNOs’ focus turns toward cost reduction rather than maximising demand growth. The decline in linear TV is much slower than expected as SVoD struggles to recapture past levels of growth also due to the uncertain economic outlook. However, the DTT platform does still evolve through investments made primarily in video coding upgrades for delivery of more HDTV content. PMSE demand continues to grow moderately. In this scenario, there are no changes to how the 470-694 MHz UHF spectrum is allocated from the early 2030s. The UHF spectrum range in the UK remains allocated to broadcast services on a primary basis and mobile allocated on a secondary basis, where PMSE continues to use interleaved DTT spectrum.
- Scenario 2, “Flexible Use” - co-primary broadcast and mobile services use for 470-694 MHz. In this scenario mobile data demand continues to grow at a similar level to recent years and rural areas experience congestion. Linear TV declines steadily, but the number of DTT households falls more slowly. In one case examined there is external investment made into the DTT platform to engineer an IMT supplemental downlink (SDL) spectrum dividend whilst at the same time maintaining payload capacity for DTT including support for some growth of HDTV delivery. However, internationally, there is significant support for 5G Broadcast and, whilst not adopted in the UK, this allows an IMT SDL eco-system to emerge. PMSE demand continues to grow moderately. In this scenario, a co-primary allocation for broadcast and mobile services is in force for the entire 470-694 MHz range from the early 2030s. This co-primary scenario would assume that any IMT services which are deployed in the band are supplemental downlink (SDL) and not FDD or TDD.
- Scenario 3, “IMT600 Band Plan” - broadcast and mobile services split in 470-694 MHz. In this scenario, mobile data demand continues to grow at a similar level to recent years and rural areas experience congestion. Linear TV declines steadily; a sizeable minority still watches linear TV, but the reach of some channels falls to very low levels. Broadcasters do question the viability of their channel mix in terms of meeting their financial and PSB objectives, resulting in some programme departures on the DTT platform. However, there is external investment made into the DTT platform to engineer an IMT600 spectrum dividend whilst at the same time maintaining payload capacity for DTT including support for some growth for HDTV content for other TV channels, driven through DTT network re-design. PMSE demand continues to grow moderately. In this scenario, the current 470-694 MHz band is divided into two ranges. The first range is between 470-606 MHz and allocated to broadcast on a primary basis with mobile on a

secondary basis. The second range is between 606-694 MHz and allocated to mobile on a primary basis. However, due to its predictable nature, high demand PMSE can also share this range with mobile through coordination. The portion allocated to mobile is designed to accommodate the 2 x 35 MHz 3GPP Band 71/n71, or the recently approved 2 x 40 MHz APT 600 MHz band plan which is awaiting assignment of a 3GPP Band number[1], or sub-sets of these band plans.

- Scenario 4, "Transition to IPTV". In this scenario, mobile data demand booms driven by a strong economic rebound to a shorter than expected recession. Users in rural areas experience significant congestion. Linear TV falls to low levels during the 2030s given the strong growth of SVoD and significant investment by the traditional broadcasters into their own online platforms. PMSE demand continues to grow moderately. The second and third scenarios are brought together for this fourth scenario, where the 470-694 MHz band is divided into two ranges. The first range is between 470-606 MHz and allocated to broadcast and mobile on a co-primary basis. The second range is between 606-694 MHz and allocated to mobile on a primary basis. The portion allocated to mobile is designed to accommodate the 2 x 35 MHz 3GPP Band 71/n71. The first range between 470-606 MHz as a co-primary allocation would assume that any IMT services are deployed in the band are supplemental downlink (SDL) and not FDD or TDD.

In our scenarios we have attempted to identify technological improvements that we believe could increase spectral efficiency and therefore accommodate users' requirements more fully i.e., the technology dividend. We would urge all stakeholders to consider how they can use UHF spectrum more efficiently as this will clearly deliver wider benefits to society.

During the rest of this decade we can expect to see operators deploy 5G services, and more 4G capacity using 700 MHz and using re-farmed 900 MHz spectrum as 3G and eventually 2G services are shut down in the 900 MHz band. Assuming the continued growth in traffic demand, and no additional low-band IMT spectrum the mobile industry may need to explore more ways of increasing spectral efficiencies from their existing low-band spectrum for the 2030s.

A key theme in all our scenarios has been the identification and recognition that the UK DTT platform could take advantage of spectral efficiency gains, whilst maintaining expected DTT payloads, and providing a spectrum dividend for IMT and PMSE services (or increasing payloads if there were viable demand from viewers and advertisers to support it). Five of the six DTT multiplexes still use MPEG2 coding. A move to MPEG4 coding by 2030 could permit repacking of TV channels into three of the five DVB-T multiplexes, with limited impact on viewers as most TV sets should be MPEG4 capable. As a benchmark, most DTT platforms in Europe make extensive use of MPEG4 coding already, A further investment into DVB-T2 would provide an additional and meaningful spectrum dividend.

Although DTT in the UK may not be technology optimised, the way in which UK MNO spectrum allocations in the sub-1GHz band have occurred means that they are also not necessarily optimised in terms of spectral efficiency. There is room for improvement, but this would require some cooperation between the MNOs to defragment and trade their respective spectrum holdings. This is something highlighted in Scenario 1 where there is no spectrum dividend for IMT.

For Scenarios 3 and 4, where IMT600 FDD is considered, there may be increased co-channel interference risks into FDD uplink from DTT transmissions in neighbouring countries maintaining DTT in the band. However, our analysis indicates that the Republic of Ireland uses only two DTT multiplexes and Belgium will only be using four out the 26 UHF DTT channels by 2030, and the Dutch DTT network is Medium Power Medium Tower. These aspects provide scope for potential movement and amendment in bilateral agreements. There is also scope for French DTT coordination, and there are also several DTT interference mitigation techniques which suggest co-channel interference risk can be minimised.

Scenario 2 with its flexible mix between IMT SDL and DTT removes the IMT/DTT co-channel interference issues associated with Scenario 3 and 4. However an IMT SDL eco-system does not yet exist and has so far not been accepted at the 3GPP standards level implying this scenario may be least likely to emerge from 2030. Furthermore, IMT SDL, whilst being more harmonious with DTT, presents additional practical challenges such as how IMT could accommodate a very wide range of spectrum (470-960 MHz) without triggering the need for more antennas at base stations. IMT SDL may also mean TV receivers, particularly those using head-end amplification, may need more complex RF filtering solutions when close to IMT base stations.

Notwithstanding DTT and IMT having scope to improve spectral efficiency, the way in which PMSE spectrum is used may allow for additional spectrum-sharing opportunities to be explored. Professional PMSE applications tend to need very high levels of high-quality spectrum in a very small number of locations, and very little or no spectrum in the vast majority of locations. This peak PMSE spectrum demand has historically been the point of contention between

[1] https://www.gsma.com/spectrum/wp-content/uploads/2022/06/Low-band-Spectrum-for-5G-Infographic.pdf

professional PMSE and IMT stakeholders of the UHF band, when UHF spectrum has been licenced to IMT at a national level. Our initial analysis of over 120,000 PMSE licenses issued by Ofcom in 470-703 MHz across the UK over the last 12-month period suggests there should be ample scope for exploring IMT/PMSE spectrum sharing opportunities. For example, there were only 53 locations in the UK which held PMSE licenses totalling more than 96 MHz at some point in the 12-month period between October 2021 and September 2022. If IMT SDL or IMT600 is not deployed in these relatively small number of locations, Professional PMSE would have access to more spectrum than currently accessible via the DTT/PMSE interleaved spectrum model.

In summary, despite technological improvements UHF spectrum will remain a scarce resource and we believe that it may not be possible to fully accommodate all stakeholder groups simultaneously. This necessitates the use of a balanced approach. To reduce social harm and costs to society, compromises in spectrum use (such as sharing) will almost certainly be required to ensure an equitable partition that safeguards societies and users' vital interests and obligations. To identify which of the scenarios is most likely to prevail we have identified several topics that we believe will merit further research.

Options on future UHF use will also likely be impacted by international developments, and the need to maintain economies of scale in equipment and terminals markets. However, many of the issues confronting the UK will also affect numerous other countries, and this may help promote common solutions. Our hope is that this report, and the scenarios that we have examined, will provide a constructive contribution to the discourse on this topic.

2. Introduction

2.1 Background

Spectrum is an important resource for the UK which generates significant economic and social benefit for UK citizens and consumers. Spectrum needs change over time in response to technology and market developments, so it is incumbent on spectrum management authorities periodically to review whether the current spectrum allocations are optimal.

The World Radiocommunication Conferences (WRCs) of the ITU are the major forum for revising frequency allocations internationally and represent an opportunity for concerted international action in responding to such changes. The Radio Regulations also detail mechanisms for coordination of spectrum use between neighbouring countries. These are important not only in limiting harmful cross-border interference but also in allowing some scope for divergence in frequency use between countries.

WRC-23 Agenda item 1.5 will consider possible regulatory actions in the use of the 470-694 MHz band. Furthermore, the main existing use, broadcasting, may face potentially far-reaching market and technological developments over the next decade which are driving a reassessment of how broadcast content is distributed.

As a result, it is appropriate for the UK to consider the future needs for the spectrum from existing uses – principally Digital Terrestrial Television (DTT) as well as Programme Making and Special Events (PMSE) use in the interleaved spectrum– and potential other uses such as mobile communications for which the spectrum is attractive in view of its propagation characteristics – allowing good wide-area coverage and indoor penetration.

It is in this context that the UK Spectrum Policy Forum retained Coleago Consulting Limited to review the industry trends that will drive the potential changes in UHF spectrum usage and to highlight the most likely scenarios for the usage of the UHF band post 2030.

2.2 Key socio-economic considerations

DTT, Mobile and PMSE all bring substantial socio-economic benefits to the UK, and each of these industries have compelling claims to UHF bandwidth.

DTT

Despite a steady ongoing shift among younger audiences from linear to non-linear content viewing, 62.5% of households still relied on DTT as of March 2020[2], either as their primary TV access mechanism or for additional TV sets within the home. While none of the scenarios examined in this report contemplate this, were DTT to disappear, this would likely deprive vulnerable social groups of TV altogether. To the extent that the majority of households would access TV content through alternative platforms, this, and any reduction in the overall DTT offering, would likely impose predominantly social rather than economic costs on aggregate.

Mobile

Mobile needs additional low-band spectrum to deliver more wide-area rural and deep indoor capacity. Mobile is a key broadband access mechanism where fixed alternatives are unavailable, and among lower-income user groups who cannot afford a fixed broadband connection. As discussed in Section 3.2, significant mobile network densification[3] in rural areas is not feasible. Without additional sub-1GHz bandwidth assignments to mobile, the quality of deep indoor coverage will suffer, and rural congestion will increase. This would risk perpetuating the Digital Divide and hamper the future potential for in-vehicle connectivity. Reduced network performance would also risk significant economic harm, given the spillovers from mobile use on wider economic activity and productivity.

PMSE

The creative industries contribute over £116 billion in Gross Value Added (GVA) to the UK, accounting for 5.9% of the economy[4]. PMSE enables output that is of high economic as well as cultural importance for the nation, and both mobile and DTT depend on PMSE for much of the content that they convey. Much of the bandwidth requirements in this sector

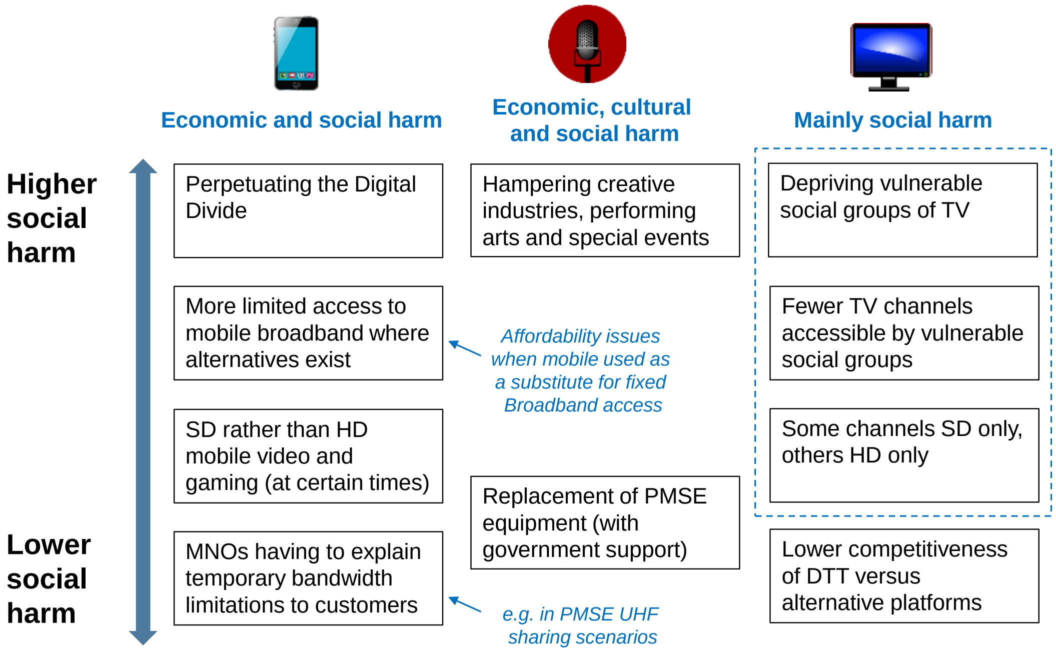
2 Source: BARB survey of TV households, April 2019-March 2020.
3 By densification, we mean the building of more mobile sites to increase network capacity (we would refer to other means of increasing capacity in any given band, such as increasing the number of sectors per site, as 'technological enhancements').
4 Source: Impact of government policy on the creative sector, 28 October, 2021, House of Lords Library (available at https://lordslibrary.parliament.uk/impact-of-government-policy-on-the-creative-sector/).

powers high-quality audio wireless microphones that are used in creative performances and content production. While PMSE has a high and growing bandwidth demand, this tends to be highly localised in time and space and is largely predictable (see Section 3.3). Nevertheless, it is essential that the industry continues to have access to significant quantities of low-band spectrum where needed. Due to increased body loss propagation characteristics typically above 1.5GHz, higher-band spectrum does not provide a suitable alternative for professional PMSE applications, and spectrum lower down in the VHF ranges is prone to interference from ignition sources, and antenna sizes can be much longer due to increased wavelength. As such the UHF spectrum range 470-694 MHz is very well optimised for body worn, professional PMSE applications.

Risk of socio-economic harm

Resources in this frequency range being limited, there are no scenarios for the future use of the UHF band that would fully satisfy the needs of each of these three industry groups. During the interviews that we conducted, stakeholders highlighted a range of adverse socio-economic effects that could arise in the event of low-band spectrum insufficiency within their respective sectors. However, not all these harms are equally severe, and it may be helpful to rank them qualitatively as illustrated below.

Exhibit 1: Potential outcomes and their relative social harm



Source: Coleago Consulting

More limited access to mobile broadband in areas where fixed broadband is prevalent might be deemed less harmful than absence of adequate broadband due to mobile network congestion in rural areas. Policy measures to address fixed broadband affordability may exist, at least in principle, where infrastructure is available. Similarly, reduced mobile video quality in areas and at times of high network congestion should be less of a concern than a comprehensive lack of connectivity for rural communities and low-income groups.

A respondent from the mobile industry emphasised the importance of consistent quality of service, which would be difficult to maintain if certain spectrum resources had to be shared with other users at certain times and locations. It seems to us, however, that while it would indeed be for the mobile network operators (MNO) to deal with customer complaints, having additional low-band resources most of the time and in most locations should still be preferable to not having access to these at all. Other mobile industry stakeholders agree with this assessment. Sharing between mobile and PMSE, for example, may still allow the industry to boost network capacity, especially in rural areas, which could help address the Digital Divide.

In the TV broadcast domain, a reduced choice of DTT channels is bound to be less harmful than being deprived of TV altogether. Likewise, offering either Standard Definition (SD) or High Definition (HD) TV programmes (rather than both) would impose less severe social costs than having access to fewer channels. A possible future reduction in DTT output would likely also make DTT relatively less competitive as a platform. This could threaten its sustainability on a standalone commercial basis, though public funding would remain an option to ensure continued operations. Threats of economic losses within the DTT-specific value-chain, provided these do not result in a loss of TV access for more vulnerable groups, might also be deemed less detrimental to society as a whole than some of the other possible outcomes.

Clearly, the object of future policy development must be to minimise harm and net costs to society. This will call for a balanced approach. Policy options on future UHF use will also likely be constrained by international developments, and the need to maintain economies of scale in equipment and terminals markets. However, many of the issues confronting the UK likely also affect numerous other countries, and this may help promote common future solutions. Our hope is that this report, and the scenarios that we have examined, will provide a constructive contribution to the discourse on this topic.

2.3 Organisation of this report

From here on, this report is organised as follows. Section 3 addresses key industry issues and trends, for DTT, mobile and the PMSE sector respectively. Within this context, we develop four main scenarios on future UHF spectrum use in Section 4. Section 5, finally, lists our recommendations for further research.

3. Key Industry Issues and Trends

3.1 DTT

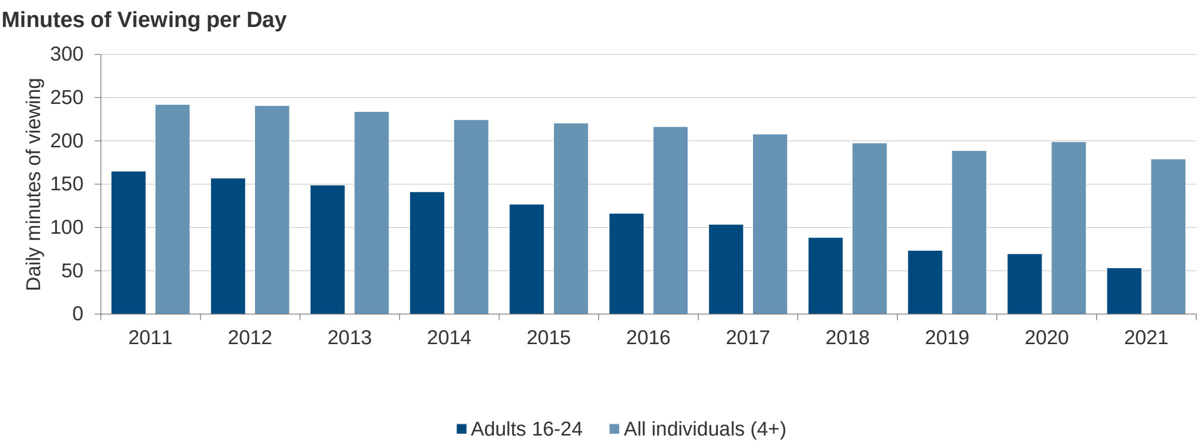
3.1.1 Trends in linear TV viewing share and DTT receiver penetration

DTT is the prime means in the UK for the delivery of free-to-air broadcasting services. These services play an important role in the UK economy both directly through the economic impact of the transmission providers and broadcasting channels, and indirectly through the economic impact on the wider ecosystem of programme production and ancillary services. DTT also provides significant social value through the delivery of public service broadcasting which provides universal access to a wide range of high-quality content free at the point of use, and reflects, represents and serves the needs of the UK's varied and diverse population.

One indication of the importance of broadcasting is its reach, i.e., the proportion of the population regularly accessing programmes or channels. For example, the reach of linear TV channels[5] (over DTT, cable and satellite) across the population as a whole was still high at 86.3% in 2021, though it had fallen from 95% in 2011. For 16–34-year-olds, linear TV reach in 2021 was lower than for the general population, but still substantial at 74.5% (down from 91.4% in 2011). In comparison, an Ofcom survey measured the reach of alternative platforms to the PSB DTT channels as follows: iPlayer (74%), Netflix (69%) and YouTube (56%) in 2022[6].

In terms of minutes of television viewed, linear TV fell proportionately more than in terms of reach. Daily broadcast TV viewing over the whole population was still substantial at 179 minutes a day in 2021, but had fallen from 242 minutes in 2011, as shown in the graph below. In contrast, it fell more rapidly, from 165 to 53 minutes a day, for 16-24-year-olds in the same period[7]. However, there has been a corresponding rise in other video services including SVOD and YouTube, so that the trend growth in total minutes watched per day has been quite moderate. As a result, the share of broadcast TV[8] in all video content – Public Service Broadcasters (PSBs) only – fell from 73% to 59% between 2017 and 2021 with a corresponding rise in SVoD and online viewing. Although there was a small shift away from SVoD in the height of the pandemic and the current cost of living crisis may also affect SVoD, we expect SVoD use to move back on trend in the near future.

Exhibit 2: Daily viewing of traditional broadcast TV



Source: BARB

In summary, although linear TV is still in a strong position today, the experience of the past ten years suggests the beginnings of a possibly fundamental shift in the consumption of video content in the UK and in most of our European neighbours. While there is much uncertainty, it is likely that linear TV will remain the most popular mode of TV

5 Ofcom, Media Nations, 2022, source: BARB
6 Both reported in Ofcom, Media Nations, 2022, (BARB data, Seven-day consolidated. Reach criteria: 3+ consecutive minutes)
7 BARB, Research criteria is 15+ minutes. As reported in Ofcom Media Nations 2022: Interactive Report, https://www.ofcom.org.uk/research-and-data/tv-radio-and-on-demand/media-nations-reports/media-nations-2022/media-nations-2022-interactive-report
8 Ofcom, Media Nations, 2022. This includes live, recorded playback and the PSB channels SVoD services.

consumption in the short to medium term, but in the longer term (beyond 2030) it is conceivable that streaming video on-demand and online consumption of video content may come to dominate.

As for the commercial sector of the broadcasting industry, it remains healthy, but it is facing competition for advertising revenue. Pre-pandemic figures show a clear decline in TV advertising in the UK, from £5.1 to £4.5 billion over 2016-19 and a rise in online advertising from £4.6 to £6.1 billion over the same period[9]. However, total TV advertising expenditure rebounded strongly in 2021 up to £4.7 billion from £3.9 billion in 2020[10]. Furthermore, Ofcom reports that broadcast video on demand (BVoD) – e.g. All 4, iPlayer and ITV Hub – advertising is growing, but from a much smaller base than for linear television (£733 million in 2021) and that streaming video on demand (SVoD) players, such as Netflix and Disney, are also considering introducing advertising supported packages.

In conjunction with a potential switch away from linear TV, there may be a concomitant shift from digital broadcasting, particularly DTT, towards platforms such as IPTV and social media such as YouTube. The proportion of households where the only receiver is DTT fell by about 40% from 26.8% in 2016 to 15.4% in 2022[11]. However, the number of households with a DTT receiver, including second or third sets where the primary set is cable or satellite, has only fallen slightly in recent years and was relatively high at 62% in 2020[12].

Given these trends, it is clearly possible that DTT may end up serving a minority of viewers in the longer term, even taking into account second and third sets. In tandem, linear TV may decline to a much smaller level which may mean that the business case for some of commercial channels on the DTT platform becomes unviable and the case for the DTT platform as a whole is further undermined.

However, while there may be compelling economic arguments to facilitate a transition from DTT in the long term, there are a number of other important factors that should be taken into account.

First, those viewers still be reliant on DTT in the future may be more vulnerable than average. For example, the over 75 age group is most likely to depend on broadcast content for some form of social inclusion and is likely to be the most reluctant to move away from DTT. In addition, those on lower incomes may find it difficult to afford upgrading their receivers and potentially having to pay higher charges for a suitable broadband connection for IPTV. Given that 8.3% of households which relied on DTT alone for television had no broadband connection in 2020 (although this may not fully overlap with low-income households) the number of people concerned may be material.

Hence, considerable social harm – social exclusion, insecurity and loneliness – could arise if the interests of these groups are not appropriately dealt with. Other considerations relevant to this policy decision would be the long-standing principles of universal access to public service television and content free at the point of use. One solution would be to retain some UHF capacity for DTT broadcasting, particularly for the PSB channels. Other options include targeted programmes to develop digital skills and targeted subsidies for upgrading receivers.

Secondly, for a transition to IPTV to be feasible, near universal broadband coverage of sufficient capacity to support the required channels would need to be in place – the coverage of the PSB DTT multiplexes is 98.5%. Currently, superfast broadband coverage, i.e., providing download speeds of at least 30Mbps, is 96% in the UK meaning over 1 million households are not yet covered. Moreover, superfast broadband take-up was only 69% where it is available. Hence, broadband coverage and affordability issues may also need to be resolved.

3.1.2 The impact of new technologies on broadcasting spectrum use

Any reduction in the UHF spectrum available for broadcasting in the UK would lead to a reduction in the number of channels that could be supported, absent the deployment of more spectrally efficient technologies. Greater spectral efficiency in broadcasting use of UHF spectrum could be achieved both within the confines of the current DTT network and through a more radical change to a different terrestrial transmission technology. The following trends and barriers to their adoption are explored in this section:

- upgrading SD channels using MPEG2 Video Coding to H.264/Advanced Video Coding (AVC) with MPEG4;
- switch to DVB-T2 across all multiplexes, with or without HEVC (High Efficiency Video Coding); and
- 5G Broadcast.

9 Ofcom, Media Nations, 2022
10 Ofcom, Media Nations, 2022
11 Ofcom, Media Nations, 2022
12 BARB, Viewing Report, June 2021

DVB-T2, is a more spectrally efficient transmission technology for digital transmission than the original DVB-T technology introduced for DTT. DVB-T2 enables higher bit rate transmission and delivers an almost 50% increase in capacity compared to DVB-T[13]. The introduction of at least the H.264/AVC MPEG4 compression standard would allow a significant increase in spectral efficiencies where MPEG2 is currently used. H.265/HEVC (High Efficiency Video Coding), as, in conjunction with DVB-T2 would offer further gains in capacity.

Some countries, such as Germany (2017) and Italy (2021-2023), are switching or have switched over their whole terrestrial TV network to DVB-T2. Germany also uses H.265/HEVC throughout its DTT platform. In the UK, DVB-T2 has been used for the transmission of a limited number of high definition (HD) TV channels since 2009. However, the original DVB-T standard has been used to transmit standard definition (SD) channels on most of the multiplexes (five out of six). Converting the remaining DVB-T multiplexes to the DVB-T2 would allow a combination of more SD and HD channels to be transmitted in the same amount of spectrum (assuming there was viable demand from viewers and advertisers to support it) or enable the current mix of channels to be transmitted over less spectrum[14].

A switch to DVB-T2 would require significant network upgrades and substantial costs for broadcasters. Viewers would also need compatible receivers to be able to receive DVB-T2 signals. However, in 2020, 88% of receivers were HD compatible[15] driven by the relatively early introduction of HD on DTT, cable and satellite and more recently by increasing adoption of large TV receivers on which the difference between SD and HD is readily visible.

An EC study forecast that the cost of replacing receivers with DVB-T2 (with MPEG4 coding) in the UK would be roughly €50 million[16] in 2022, assuming a 7-year natural replacement cycle. The same study found that a DVB-T2 receiver replacement to HEVC instead of MPEG4 would add an extra to 130% to replacement costs (on average across EU member states).

On this basis, the costs of a transition to DVB-T2 appear significant, but moderate compared to the overall size of the DTT sector. However, a sizeable minority has yet to upgrade. As discussed in the previous section, these viewers are likely to be older and on lower incomes than average, hence a programme of government support may be necessary to encourage them to switch. For comparison, the Italian government made available a package of €100 million to support viewers in Italy's transition to DVB-T2.

5G Broadcast is a potential converged mobile and TV broadcasting service, which would extend the delivery of broadcast content from fixed receivers to mobile devices, including in-vehicle systems. The service would be delivered over 5G using either a broadcast network, a cellular network or an amalgam of the two. However, 5G Broadcast is still in the early stages of development though a significant number of trials and testbeds having taken place including 5G VISTA in the UK and 5G MEDIA2GO in Germany[17]. Much remains uncertain about the ideal use cases for the platform, its market positioning and its chances for commercial success.

Our research and stakeholder discussions have shown that one of the initial drivers of interest in 5G Broadcast has been to deliver live content – sports, news, concerts – based on the belief of an unmet demand for live broadcasting since consumers may be on the move when a live event is taking place. Another use case being considered is to use 5G Broadcast as a distribution channel for public information during an emergency or natural disaster.

Opinion varies as to whether 5G Broadcast would develop as a complementary service to broadcast TV or as a replacement for the DTT network in the longer term. Some commentators reconcile these views by suggesting 5G Broadcast could begin as a complementary service then potentially evolve later on to replace DTT.

As yet, the bandwidth delivered by 5G Broadcast (30Mbps) has been unable to match that provided by DVB-T2 (c.40Mbps depending on encoding)[18] and 5G Broadcast requires a higher signal to interference and noise ratio. Trials have also found that, in order to serve mobile devices, a significantly higher power level is necessary than for rooftop aerials. This requires the deployment of additional Low Power Low Tower (LPLT) sites alongside the High Power High Tower (HPHT) of the current broadcast networks and the additional sites are most likely to be required in urban areas.

13 EBU, "Frequency and Network Planning Aspects of DVB-T2", 2011 https://tech.ebu.ch/docs/news/2012_01/wrcdocs/Planning%20aspects%20of%20DVB-T2%20-%20EBU%20TECH3348%20-%20May%202011.pdf

14 We note there has been some activity in broadcasting Ultra High Definition (UHD) over DTT – for example, the French Open Tennis Championships since 2020 and 2022 World Cup games in Spain. Moreover, the emerging ASTC 3.0 standard in the United States provides more capacity than DVB-T2 and enables 4K or UHD image quality. However, in our view there is not yet enough evidence to judge whether significant demand for UHD over DTT might develop in the UK.

15 https://www.digitaltveurope.com/2020/05/13/uhd-tv-penetration-seeing-phenomenal-growth-in-uk-says-ses/

16 VVA & LS telcom for the EC, "Study on the use of the sub-700 MHz band (470-694 MHz)", 2022

17 For more details of 5G Broadcast trials and projects see: EBU TR 044, "Trials Tests and Projects Relating To 4G/5G Broadcast Supported by European PSB", 2022, https://tech.ebu.ch/docs/techreports/tr044.pdf

18 VVA & LS telcom for the EC, "Study on the use of the sub-700 MHz band (470-694 MHz)", 2022

Hence, a 5G Broadcast network could incur greater costs than a traditional broadcast network. Although, there is little direct evidence to date on the level of these costs, there is some indicative research. An EBU study[19] referenced by the European Commission[20] found that, in Germany, an LPLT network with a similar spectral efficiency to DVB-T2 would cost approximately seven to eight times than the cost of the DTT network. This 2014 study considered the network density required to achieve a similar capacity for mobile / light indoor reception over an LPLT network (LTE) compared to existing portable reception over the German DTT network. We reiterate that this study was for a different technology to 5G Broadcast, and that further study of the costs of a 5G Broadcast network compared to DTT would be desirable to inform discussion of its potential.

The potential need for additional sites compared to a traditional DTT network may have implications for the 5G Broadcast business model. Would a broadcaster itself deploy the additional sites needed to serve mobile devices given the substantial costs involved and the ongoing decline in linear TV? Or would it make more sense for at least the fixed costs of the network (but not the additional capacity costs) to be shared with mobile operators or independent tower companies? A variety of arrangements could be used from purchasing dedicated capacity upfront to a capacity as a service model.

Another challenge to be overcome for 5G Broadcast to become a replacement for DTT, would be to ensure that the traditional receiver (connected to the rooftop aerial) is 5G Broadcast compatible. This would require sufficient time and forward planning for compatible TV sets to be manufactured and to penetrate across households through the normal replacement cycle. Even so, similar issues would likely arise as for a DVB-T2 transition, with digital literacy and affordability issues for a significant minority of viewers.

3.2 Mobile

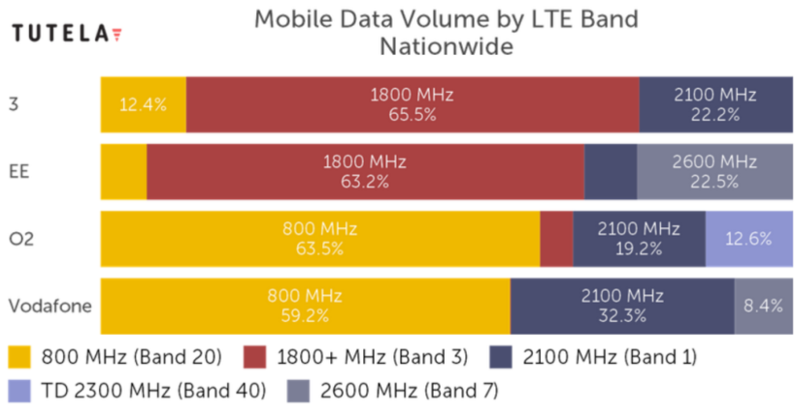
Due to its superior propagation characteristics, conferring significant wide-area and indoor coverage benefits, spectrum below 1GHz is a very important resource for mobile. As outlined below, existing sub-1GHz allocations carry a disproportionate amount of current mobile traffic per MHz of available bandwidth. This reflects the fact that much of the mobile usage occurs in locations that are hard to reach with higher bands – notably indoors and in rural areas (albeit the latter tends to account for a small proportion of total mobile consumption). If the unrelenting growth in total mobile broadband demand persists, and without effective mitigation, pressure on the low bands would continue to increase.

In section 3.2.1 below, we examine the proportion of traffic carried in low and mid-bands. We focus on 4G for the sole reason that we were unable to source information on utilisation by band across other technologies. Total existing mobile spectrum holdings in low and mid bands are considered in sections 3.2.2 and 3.2.3, within the context of the overall rise in demand for mobile capacity, and technological developments. Impact and mitigation are discussed in section 3.2.4.

3.2.1 Mobile utilisation of low-band spectrum in the 4G era

Crowdsourced network data published by Tutela suggests that the 800 MHz band, accounting for around 13% of 4G bandwidth, carried over a third of total 4G traffic in the UK in 2020.

Exhibit 3: Proportion of 4G traffic carried by band and by operator in the UK



Source: Tutela based on data from March-August 2020

19 EBU, "Assessment of available options for the distribution of broadcast services", 2014 https://tech.ebu.ch/docs/techreports/tr026.pdf

20 VVA & LS telcom for the EC, as above

The marked difference between 3 UK and EE versus O2 and Vodafone, in the proportion of 4G traffic carried by 800 MHz is likely explained by the following factors.

- O2 and Vodafone's 800 MHz holdings are double those for EE and 3UK, yielding a higher proportion of bandwidth this band (albeit the difference in %800 MHz bandwidth with 3 UK is narrower, as shown in Exhibit 4 below);
- A 2 x 10 MHz 800 MHz channel (O2 and Vodafone) is more efficient spectrally than a 2 x 5 MHz channel (EE and 3UK), yielding both higher net capacity per MHz and higher channel data-speed performance;
- 3 UK (and to a lesser extent EE) may plausibly have deployed 800 MHz less widely at the time, as the cost per MHz for an inefficient (and less performant) 2 x 5 MHz channel is around double that for a 2 x 10 MHz channel, and many sites originally built for 1800 MHz and above needed costly rebuilds to carry the larger 800 MHz antennas[21];
- EE and 3 UK's network grids are denser, as these were originally designed for higher bands (with inferior coverage characteristics) than O2 and Vodafone's, which were originally built for 900 MHz – as a result, EE and 3 UK may plausibly be able to address a higher proportion of their respective demand with higher bands.

The 4G spectrum holdings aligned to Tutela's analysis are shown below:

Exhibit 4: Spectrum deployments in 4G (total MHz uplink plus downlink)

	BT/EE	O2	Vodafone	3 UK	Total
800 MHz	10	20	20	10	60
1800 MHz	80	10	-	30	120
2.1 GHz	30	20	30	20	100
2.3 GHz	-	40	-	-	40
2.6 GHz FDD	80	-	40	-	120
2.6 GHz TDD	-	-	20	-	20
Total bandwidth (MHz)	200	90	110	60	460
% Sub1 GHz	5.0%	22.2%	18.2%	16.7%	13.1%

Source: Coleago based on Pedroc analysis[22]

Taking shares of customers as a rough proxy for shares of 4G data traffic, we obtain a weighted average utilisation per MHz in the 800 MHz band in the UK that is **3.8x** that for higher bands – with over a third of UK 4G traffic carried by 800 MHz. This underscores the significance of low-band holdings for mobile services.

3.2.2 Growing demand for sub-1 GHz bandwidth

Following the awards of 700 MHz, 1400 MHz and 3.4-3.8 GHz spectrum to mobile, MNOs' sub-1 GHz holdings now account for around 19% of their total low and mid-band holdings (17% if we exclude the 700 MHz SDL, which still lacks a viable international ecosystem).

Exhibit 5: Current UK mobile spectrum holdings (total MHz uplink plus downlink)

	BT/EE	VMO2	Vodafone	3 UK	Total
700 MHz	20	20	-	20	60
700 MHz SDL	20	-	-	-	20
800 MHz	10	20	20	10	60
900 MHz	-	35	35	-	70
Total sub1 GHz	50	75	55	30	210
1400 MHz	-		20	20	40

21 EE may plausibly have deployed 800MHz more widely than 3 UK at the time, because of EE's need to meet higher network availability metrics under its Emergency Services Network (ESN) contract with the UK government. Note that as of today, we believe that operators' policies both in the UK and across Europe are generally to deploy sub1GHz spectrum on all sites in which this is feasible.

22 Source: https://pedroc.co.uk/content/uk-commercial-mobile-spectrum, accessed in October 2022.

	BT/EE	VMO2	Vodafone	3 UK	Total
1800 MHz	90	10	10	30	140
2.1 GHz	40	20	30	29	119
2.3 GHz	-	40	-	-	40
2.6 GHz FDD	100		40	-	140
2.6 GHz TDD	-	25	20	-	45
3.4-3.8 GHz	80	80	90	140	390
Total mid bands	310	175	210	219	914
Total bandwidth (MHz)	360	250	264	249	1,123
% Sub1 GHz	13.9%	29.9%	20.7%	12.0%	18.7%

Source: Ofcom

Nevertheless, mobile-industry stakeholders have indicated that they continue to experience significant low-band congestion, even though operators actively direct traffic to higher frequencies where possible, only defaulting to the sub-1GHz bands when these are the only resources customer devices can “see”.

Pressure on low-band spectrum is likely to increase dramatically if the unrelenting growth on overall mobile data traffic persist, which we believe is plausible, albeit future projections are of course subject to uncertainty. Ofcom’s Communications Market Report 2022 suggests that total mobile data traffic grew by 36.2% between 2020 and 2021, reaching an average of 6.9GB per capita in 2021. Ericsson projects average annual growth in traffic of 24% between 2021 and 2027 – implying traffic 3.6x 2021 levels if the UK follows the same trend[23].

We have not seen external forecasts beyond 2027. However, by 2030, which is the earliest data by which scenarios for future UHF band use are being considered, these forecasts imply that traffic will have grown to:

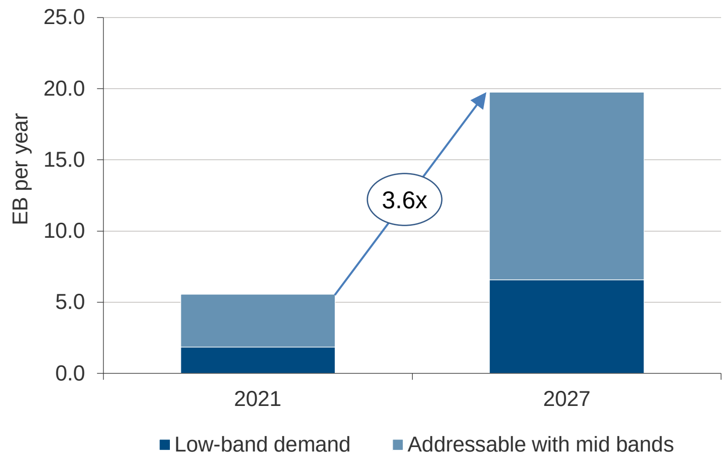
- 7x 2021 levels if demand continues to grow by a 24% compound annual growth rate (CAGR) beyond 2027; and
- 5x 2021 levels if the average annual growth rate were to halve after 2027.

And by 2035, traffic will have grown to:

- 19x 2021 levels if demand continues to grow by a 24% compound annual growth rate (CAGR) beyond 2027; and
- 9x 2021 levels if the average annual growth rate were to halve after 2027.

This is broadly consistent with industry expectations of 100 GB mobile data consumption per capita within 15-20 years[24].

Exhibit 6: Increase in total UK mobile data traffic 2021-2027



Source: Coleago consulting based on Ofcom data and Ericsson projections

23 Source: Ericsson Mobility Report, June 2022. Note that Ericsson’s estimate for Western European mobile data traffic growth is very close to the figure implied by Ofcom for the UK between 2020 and 2021, suggesting similar trends across the UK and Western Europe.
24 We have seen multiple projections by operators internationally within the context of spectrum auctions that suggest this.

Assuming the growth in demand is uniform across the network, we would expect a similar proportion of future traffic being hard to reach with mid bands (above 1 GHz and below 6 GHz) – roughly a third, according to our 4G analysis in Section 3.2.1 above. The issue is that there is significant scope to the capacity per MHz for mid-bands, using technology enhancements, as outlined in Section 3.2.3 below, but there are very few opportunities to do so in sub-1GHz bands.

Given this projected growth in demand, and without either additional sub-1GHz spectrum or effective mitigation, severe congestion is likely to be felt by 2030 in the low bands in particular. The recent award of 700 MHz spectrum to mobile represents a significant increase in low-band capacity relative to 2020 (the time of our 4G analysis), albeit one should bear in mind that traffic will likely have grown by around 70% between 2020 and 2022[25]. Further refarming of 900 MHz spectrum from 2G to 5G and from 3G to 5G will also contribute to low-band capacity (albeit some resources will need to be kept for legacy traffic[26]), as will future refarming of 800 MHz from 4G to 5G. Even accounting for the increases in spectral efficiency described below, these increases in low band capacity are likely to fall well-short of projected demand by 2030 and even more severely so by 2035.

The only remaining route to increase low-band capacity would be to densify the network. As discussed in section 3.2.4 however, the scope for this is curtailed by both economic and practical factors.

3.2.3 Technological developments

5G already improves on the performance and capacity achievable with 4G, for a given configuration – typically increasing capacity per MHz by around 15%[27]. Two further approaches to improving spectral efficiency include technology enhancements, such as sectorisation and higher-order Multiple-Input/Multiple-Output (MIMO) antenna systems.

Adding a fourth sector to a three-sector site may extend the effective site capacity from a given band by around 40%[28]. This result (more than the one-third increase in the number of sectors) is due to the uneven distribution of traffic across the site.

Sectorisation and higher-order MIMO both support 4G and 5G. Accordingly, massive MIMO will help address the growing demand for 4G capacity in the near term, while providing future 5G air-interface functions that can be activated through software upgrades.

A conservative rule of thumb is that each doubling of the MIMO order above 4 x 4 MIMO (i.e., doubling of the transmit and receive antennas on each sector) increases capacity by a factor of around 1.3x. For example, 64 x 64 order MIMO (‘massive MIMO’) can generate over 3.3x more capacity per MHz than a 2 x 2 MIMO configuration (the base for 4G and 5G)[29]. Some operators and vendors are even more optimistic about the MIMO uplift.

Given that lower band antennas are larger and due to space limitations on sites, increased sectorisation is easier to implement in mid- and high bands. The same is true for higher MIMO orders, there may be scope for up to 4 x 4 deployments in sub-1GHz bands, as discussed further in 4.1.1. Note that while 4 x 2 MIMO is likely to be the best achievable in low band with mobile handsets (due to device-antenna constraints), 4 x 4 might be feasible for connected vehicles and some future rural fixed-wireless applications that rely on low band for connectivity.

Based on current mobile industry holdings and assuming 5G is deployed in all bands with 64 x 64 MIMO in 3.5 GHz and 2.3 GHz, 8 x 8 MIMO in 2.6 GHz TDD, and 4 x 4 MIMO in all other bands[30], sub-1GHz bandwidth would account for less than 10% of potential site capacity. This percentage could be even lower if even higher order MIMO is assumed in the 3.5GHz band.

25 With 36.6% growth between 2020 and 2021, as outlined above, compounded by growth likely in excess of 24% between 2021 and 2022, we obtain an increase of around 70% between 20wo and 2022.

26 In particular, legacy machine-to-machine devices may require some spectrum to be kept on 2G or 3G for some time yet, albeit we consider this a second-order issue for overall spectrum needs.

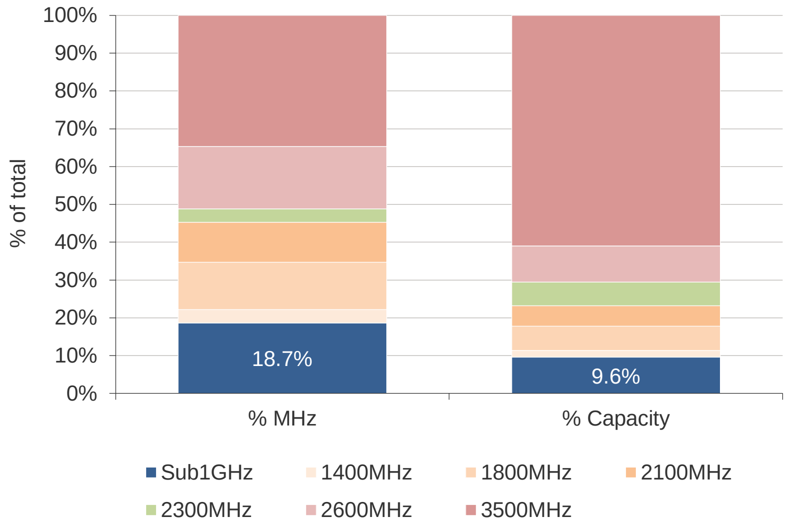
27 See also https://tools.pedroc.co.uk/4g-speed/ and https://tools.pedroc.co.uk/5g-speed/

28 Source: Coleago discussions with operators.

29 We assume a downlink throughput of 1.8 bit/s/Hz for 2x2 MIMO and 2.2 bit/s/Hz for 4x4 MIMO. 64 represents a 4-fold doubling of 4. The capacity per Hz for 64x64 MIMO is calculated as 1.3×1.3×1.3×1.3×2.2 =6.0 bit/s//Hz which is 3.3x that for 2x2 MIMO. The 1.3x multiplier reflects a view expressed to us by the GSMA.

30 This yields an optimistic outlook for the existing sub-1 GHz holdings, yet the potential capacity per site from low bands still remains below 10% of the total achievable).

Exhibit 7: % Potential capacity per site by frequency range



Source: Coleago Consulting

There is also scope to further enhance total network capacity by deploying small cells, however these tend to be focused on urban areas and are not suitable for sub-1GHz. In short, there are ample opportunities to extend the capacity provided by mid bands, but very few that address rural wide-area and deep indoor coverage quality.

3.2.4 Impact of low-band spectrum insufficiency and possible mitigation

With industry expectations that total mobile data demand will exceed 100 GB per capita (15x current levels) within 15-20 years, the mobile industry is likely to eventually "run out of road" – whether or not extra sub-1GHz spectrum is made available for mobile during the intervening period.

This is of course only the case if the rapid growth in mobile data demand does indeed persist in the years ahead, and assuming the distribution of traffic across time and space remains as it is today. Under these assumptions, which we believe are plausible, this could result in a significant proportion of future demand not being adequately served in the absence of effective mitigation. This could be very costly to society, given the high reliance that businesses, consumers and, increasingly, devices, place on mobile connectivity. Rural communities would no longer be able to rely on mobile as a substitute for fixed broadband access, as increasing levels of rural network congestion degrade the service. Low-band congestion would likely also hamper the future potential for in-vehicle connectivity across the country.

Where fixed broadband is available for backhaul, indoor coverage solutions may address mobile capacity needs within commercial premises. Multi-operator systems, operated by accredited neutral hosts, would ensure seamless provision of services to customers within these locations. Residential premises are harder to deal with, albeit signal repeaters and femtocells may offer a possible avenue. A concern expressed by mobile industry stakeholders is that incorrect installation or use of these by consumers could lead to complaints which are difficult and costly for mobile operators to address – especially if the problem lies with broadband connections provided by other parties. Nevertheless, in the absence of better alternatives, this might not be insurmountable. Yet, femtocells would not address indoor capacity for (lower income) households that use mobile as a substitute for fixed broadband, since these require a fixed broadband for backhaul as does Wi-Fi.

Nor would hotspot-type solutions address demand in sparsely populated areas, where premises are far apart, or the future needs of connected vehicles. With respect to the latter, a report for the German telecoms regulator states that "at least 50 MHz will be required for mobile radio applications in the spectrum below 1 GHz to support automated driving in rural areas"[31].

31 Our translation, from 'Perspektiven Zur Nutzung Des Uhf-Bands 470-694 Mhz Nach 2030, Studie im Auftrag der Bundesnetzagentur', Goldmedia GmbH Strategy Consulting and Fraunhofer-Institut für Integrierte Schaltungen IIS, November 2021. Stakeholders participating in this study have suggested that enhanced DTT to vehicles might substitute some of the demand for mobile-to-vehicle data. While we agree with the principle, a discussion on the extent to which this could mitigate mobile spectrum constraints is beyond the scope of this report.

Sub-1GHz insufficiency may be felt most acutely in rural communities, beyond the reach of fixed broadband. In theory, additional low-band capacity could be delivered by deploying more radio sites in those areas. But with demand in those same areas increasing by over an order of magnitude, the levels of future densification required would be vast. Moreover, rural sites tend to be far more expensive to build and operate, due to more complicated power provision and backhaul transmission. The commercial business case for such infrastructure build is non-existent: despite explosive growth in mobile consumption, industry service revenues have been in decline over the past decade[32], and mobile operators often struggle to earn their cost of capital[33]. Nor is it clear that public funding of rural densification could provide a comprehensive solution. The Mobile Infrastructure Project (MIP) launched by the UK government in 2011, for example, only delivered 75 rural sites (covering 7,200 premises) against an original target of 575 (intended to cover 60,000 premises)[34].

A number of stakeholders outside the mobile industry also raised the Shared Rural Network (SRN) initiative as possible mitigation for a lack of low-band resources for mobile. However, the main objective of SRN is to address not-spots and partial not-spots. While expanding the footprint of mobile communications is unquestionably of high importance, we do not consider SRN a substitute for bandwidth – which would be needed to address future capacity needs rather than for coverage *per se*. A further point raised was that new building regulations result in premises being intrinsically difficult to penetrate with either low or higher band spectrum. While this may affect new builds, this issue is unlikely to bear on much more than 1% of premises nationally over the time-horizon under consideration, and we do not consider it material to the present study.

Future reorganisation including defragmentation of the sub-1GHz mobile band-plan could improve the efficiency with which these resources are used and deliver an uplift of 20-40% to capacity, as outlined in 4.1.1. However, this would certainly still fall far short of needs, and is highly unlikely to materialise within the medium-term timeframe under consideration within this report.

Access to additional sub-1GHz spectrum, even on a shared basis, would provide much needed respite to operators and their customers. It would delay the point at which the industry does indeed “run out of road” and might allow for smoother (and economically less disruptive) longer term mitigation.

3.3 PMSE

3.3.1 The diversity and high-level economic importance of audio PMSE

Audio PMSE use in the UHF band comprises a number of different services including radio microphones and in-ear monitors (IEMs) which are used by musicians and television presenters to hear a personalised feed of music or instructions, in support of live performance or in content production.

Significant economic value added is associated with the activities that audio PMSE helps support. For example, the film industry contributed an estimated £6 billion to UK Gross Value Added (GVA) in 2017 (on a turnover £14.8 billion)[35], theatre generated £1.3 billion in revenue in 2018[36], and festivals and concerts generated revenues of £1.1bn and £1.3bn revenues in 2017[37]. Though only a portion of these revenues should be attributed to PMSE (and it is difficult to determine what this proportion should be), PMSE has become an integral part of delivering these services. Without PMSE, the attractiveness and value of many cultural, sporting and other events, and of similar activities in the broadcasting sector would be diminished.

Audio PMSE users are strikingly diverse. They run the gamut from television coverage of the largest, premium events such as the Eurovision song contest and international sporting championships, to festivals and major theatrical productions, to other commercial users such as trade fairs, local theatre (1,100) and film/video/TV post-production (16,240 companies) to non-commercial users such religious venues (40,000 churches and 1,825 mosques) and schools (32,000).

32 Based on mobile service revenue estimates obtained from successive Bank of America Merrill Lynch Global Wireless Matrices.

33 For example, Finbox.com estimates Vodafone Group’s return on invested capital (ROIC) at 2.9%, significantly below its cost of capital (WACC), estimated between 4.8% and 7.9% by Valueinvesting.io.

34 Source: DCMS, ‘Mobile Infrastructure Project Impact and Benefits Report’, July 2017.

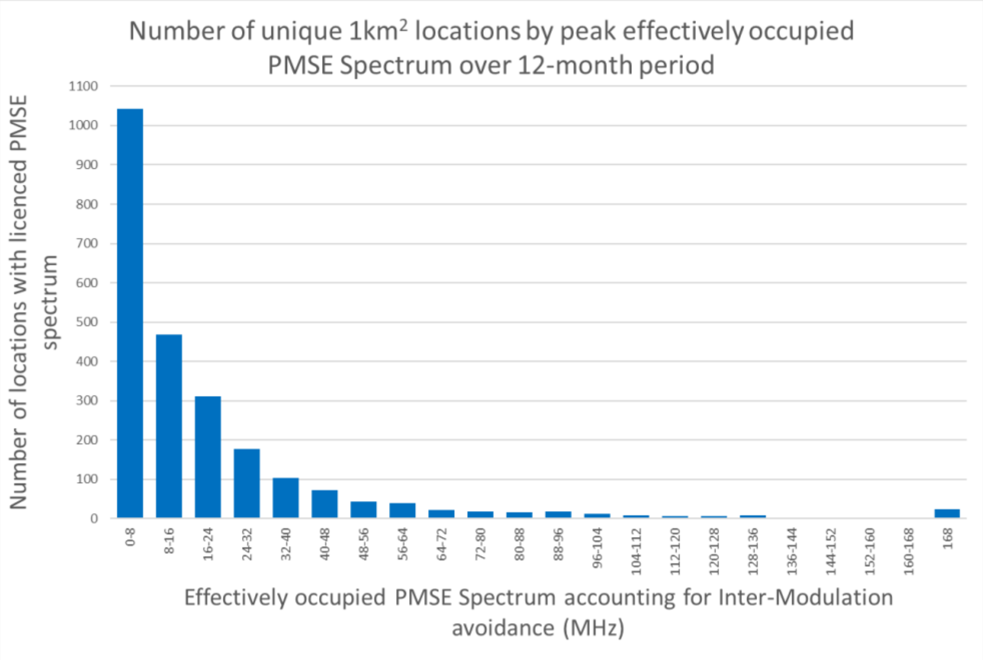
35 BFI, “The UK Film Economy”, 2018, https://www2.bfi.org.uk/sites/bfi.org.uk/files/downloads/bfi-uk-film-economy-2018-12-19.pdf. GVA is the amount by which a sector adds to economic value and is estimated as the revenues of the end-product/service minus the costs of the inputs (raw materials, components and services) used to make the product/service.

36 Venues represented by the Society of London Theatre and UK Theatre, https://solt.co.uk/about-london-theatre/press-office/solt-and-uk-theatre-continue-to-work-with-government-to-find-solutions-for-the-theatre-industry/

37 Plasa, Entertainment Technology Industry Research Report 2017/18

The diversity of PMSE users is also reflected in the uneven distribution of locations in terms of their spectrum usage. The graph below, based on our processing of Ofcom data of over 120,000 PMSE licenses in 470-694MHz over the period of Oct 2021 to Oct 2022, shows that fewer than 2.5% of 1km^2 locations occupied more than 104MHz of unique spectrum at some time over the year. Occupied spectrum in this context takes into account the effective increase in PMSE spectrum needs due to intermodulation interference avoidance, which is necessary for many large-scale events using PMSE

Exhibit 8: Distribution of unique locations by effective total peak PMSE spectrum occupancy over 12-month period



Source: Ofcom and Coleago

This translates into spectrum demand as follows. For the largest scale events and shows, the spectrum required to support audio PMSE is at or near the limit of that available in the UHF band in Europe and a number of other similar markets. For example:

- Sennheiser reports from Australia that large scale shows such as the musical Hamilton can routinely use over 40 wireless audio channels simultaneously and that frequency coordination at this scale will typically consume most of the 184 MHz of available UHF spectrum in Australia[38].
- Swiss broadcaster SRF estimates a requirement of 174 MHz for the most demanding events such as Eurovision and the Tour de France, though for limited periods only, and a daily requirement of up to 115 MHz for the next level of large event venues[39].

However, while larger scale productions require significant amounts of spectrum for audio PMSE, demand is highly localised and predictable. PMSE demand tends not to be in rural areas, apart from a few one-off events such as Glastonbury. Hence, in rural areas, the overlap between PMSE and potential future users who might be interested in gaining access to the spectrum in the medium term, such as IMT, is likely to be limited. In some urban areas, however, such as the West End of London, there will be a considerable overlap between PMSE use and potential future uses. In other urban areas, PMSE use may be periodic but predictable, hence the overlap with potential future uses may be delimited temporally, i.e., according to when audio PMSE is in use. In summary, where the overlap between PMSE and potential future demand from IMT is limited, there may be a case for opening up access to UHF spectrum (on a geographic or time-limited basis) but predicated on protecting PMSE use. This is certainly likely to be the case in rural

38 Submission from Sennheiser Australia Pty Ltd To Media Reform Green Paper, Modernising Television Reform in Australia, May 2021
39 VVA & LS telcom for the EC, "Study on the use of the sub-700 MHz band (470-694 MHz)", 2022. This is similar to the EU's estimate of a requirement of 150 MHz for the largest events [GIVE REF].

areas. A priori, there would therefore appear to be significant scope for sharing of any additional UHF spectrum between PMSE and IMT, which could provide an avenue for mobile to better address connectivity needs in those areas – which would help address the rural Digital Divide.

3.3.2 Future PMSE growth

PMSE demand has been steadily growing particularly for the higher tier commercial use such as festivals, theatre and live coverage of sporting events. This growth has been driven by an increasing level of microphone and IEM use across the performers or participants in order to enhance the quality and sophistication of the entertainment provided to the audience. Recent years have also seen significant developments in the nature and scale of reality TV and talent shows which are making much greater use of microphones to enhance their ability to make engaging content and improve the viewing experience.

Another example of increasing use of audio PMSE demand has been the growth of recording and live streaming of theatrical productions for the home, cinemas and other venues. Moreover, at home viewing of cultural events was given a boost during the pandemic. Now, live streaming and on-demand are seen as important streams of additional revenue alongside public performances which have recommenced.

As a result of growing demand, the largest scale events, which are already experiencing some spectrum constraints, would face increasing congestion in the future, assuming spectral efficiency remains the same. Some commentators predict that as much as 224 MHz may potentially be required for major events in the future, i.e., the whole sub-700 MHz UHF band[40].

In addition to high tier users' increasing demand for PMSE, small and non-commercial user demand is also growing and professional PMSE equipment is increasingly being used, though the gap in requirements between high and low tier users remains. This trend may limit the ability of these lower tier users to use smaller blocks of spectrum, such as guard bands, that are already unsuitable for the larger commercial users.

3.3.3 Recent technological advances

Significant improvements in audio PMSE spectrum efficiency have been made in the past. For example, as a result of the introduction of digital technology, equipment is now able to deliver around 2.5[41] to 3 times the number of audio channels in a fixed amount of radio spectrum whilst achieving acceptable levels of quality (though analogue PMSE does still retain some performance advantages over digital). In addition, the development of very linear power amplifiers has increased spectral efficiency of PMSE equipment by improving its intermodulation performance.

However, the amount of spectrum available for PMSE has fallen by nearly 50% due to the clearance of broadcasting from the UHF band to release the 700 and 800 MHz digital dividends. Hence, recent technological advances have only enabled audio PMSE users to compensate for the decline in available UHF spectrum and will not help meet future growth in PMSE demand or facilitate further reductions in the UHF spectrum available for PMSE.

3.3.4 The potential for further technological progress

Research is currently underway into several new technologies which could lead to further improvements in spectral efficiency for audio PMSE, though the outlook is far from certain at this stage. In particular, we focus on the following two technologies which we believe currently hold the most promise:

- Wireless Multichannel Audio Systems (WMAS); and
- 5G for PMSE.

WMAS allows for easier coordination and greater allocation efficiency in using multiple devices over a relatively wide block of spectrum (6,7,8,10,20 MHz) compared to narrowband audio channels. WMAS is particularly effective for larger scale PMSE users managing large numbers of devices. It allows statistical multiplexing, and it can optimise for devices with differing performance requirements – e.g., quality, latency, robustness – enabling further efficiency gains. Hence, WMAS can significantly increase spectral efficiency. However, if PMSE spectrum is fragmented, so that a sufficiently wide block of contiguous spectrum cannot be obtained, the benefits of WMAS will not be achieved.

Views on the size of the potential efficiency gains vary, but the general consensus is that gains will be significant but not revolutionary. For example, ETSI predicted that efficiency could increase by about 50% in comparison to narrowband

40 VVA & LS telcom for the EC as above
41 RSPG, 2017

systems[42]. Other commentators suggested that WMAS could lead to a rough doubling in the number of audio channels that could be supported in one TV channel bandwidth.

However, WMAS is still an emerging technology. It is uncertain whether it will gain the level of traction in the market necessary to generate the economies of scale needed to drive down costs, especially as it is only one of several innovations, e.g., wireless 3D audio capture, competing for commercial adoption by equipment manufacturers. If and when WMAS establishes a firm position in the market, it may still take five to ten years for WMAS-compatible equipment to diffuse through the user base. Although, if high tier users are becoming spectrum constrained, they will have an incentive to take-up WMAS equipment more quickly.

Research is being carried out on the use of 5G for audio PMSE[43]. The key performance requirements that 5G will have to meet are the demanding levels of latency and reliability necessary for the use of audio PMSE in live and recorded performance. Latency is critical because if it rises above a certain level, musicians will be unable to synchronise with other performers. Reliability is essential for live performances, because any failure, even temporary, may be noticed by the audience and detract from their enjoyment, with a knock-on effect on what audiences will be willing to pay.

Nokia and Sennheiser conducted a testbed for PMSE over 5G in 2021[44]. They reported a 7ms application latency for 2-way transmission from microphone to receiver unit and back to the artist's IEM. Although, the required application latency for PMSE is 4ms or less, Nokia and Sennheiser concluded that 5G held promise for PMSE, though further improvement was necessary to prove it could meet the latency requirements. They also noted that commercialised equipment may offer superior performance to the equipment used in the testbed and this would help to bridge the gap.

Nokia and Sennheiser also noted that 3GPP standardised URLLC enables the reliability requirements for PMSE to be met with Release 15 providing successful packet delivery of 99.999% or higher and work was continuing in Release 16 to reach 99.9999%.

In practice, a number of commercial issues would need to be resolved to enable PMSE to move to 5G.

- Significant development in commercial, off the shelf equipment would be necessary. There would need to be sufficient demand to give manufacturers confidence of the economic viability of including 3GPP Release 16 URLLC standards within their equipment.
- 5G networks would need to deploy additional capacity to accommodate PMSE traffic and meet its performance requirements. If provided over the public network, mobile operators would need to make significant investment in their networks and deploy advanced features such as network slicing. If a non-public network solution for PMSE were economically viable, dedicated spectrum in the appropriate frequency range would need to be made available.
- Regardless of whether audio PMSE were carried over a public or a non-public network, a clear business model would need to be established so that services are provided to users at a reasonable price (taking into account the costs of upgrading equipment) and network operators gain an appropriate return on their investment.

3.3.5 Prospects for additional spectrum bands for PMSE

An alternative to deploying new technologies to provide more capacity for PMSE would be to identify new spectrum bands. Any new spectrum would have to lie in the sub-1.5GHz range in order for audio devices to function acceptably. As stated earlier, this is because many audio PMSE equipment is body worn and, as a result, radio waves interact with the human body. At frequencies above 1.5GHz, this interaction can lead to problems with the directivity of the signal and body absorption.

International harmonisation is also an important factor in introducing new bands for audio PMSE, especially for international PMSE users. Manufacturers are less likely to supply equipment for spectrum that is only available in a few countries. Moreover, any equipment that is produced for a limited market will be relatively expensive due to the weaker economies of scale. This phenomenon is apparent in the UK, where the UK has pioneered the 960-1164 MHz band for audio PMSE (a few other countries are considering following suit). Although there is some professional use of the band in the UK, take-up is low due, in part, to the cost of the equipment.

42 ETSI TR 103 450 V1.1.1 System Reference document (SRdoc); Technical characteristics and parameters for Wireless Multichannel Audio Systems (WMAS), 2017, https://www.etsi.org/deliver/etsi_tr/103400_103499/103450/01.01.01_60/tr_103450v010101p.pdf
43 E.g. the PMSE-xG project, http://pmse-xg.research-project.de/index.html
44 Nokia, Sennheiser white paper, January 2021, "Low Latency 5G for Professional Audio Transmission" https://www.bell-labs.com/institute/white-papers/low-latency-5g-professional-audio-transmission/

Furthermore, there has been opposition in CEPT to sharing between PMSE and aeronautical services in the 960-1164 MHz band. Established positions would have to be revised substantially for any progress towards wider international adoption of the band for PMSE.

4. Main Spectrum Scenarios

The backdrop to each scenario will be a certain combination of the trends and issues that we outlined in Section 3. To provide some context on how these trends inform our scenario development, we set out one potential combination of trends under which each scenario could emerge. However, this is one of several such combinations and is only intended to be indicative.

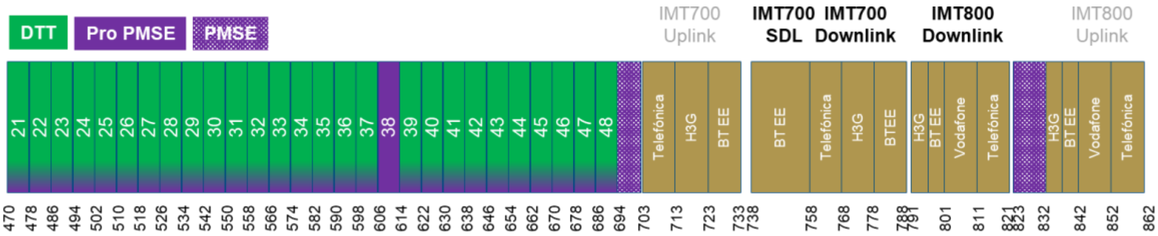
In each scenario, we then describe how the UHF band would be allocated to different services, we provide an overview of any relevant international coordination issues and describe the high-level outcomes for IMT, DTT and PMSE. Next, we discuss in detail the implications for each of the three services before providing some concluding remarks.

4.1 Status quo – no change in allocation

Our indicative set of key trends for this scenario is as follows. Mobile broadband demand continues to grow at a similar level to the previous five years, but IoT growth is slower than expected. MNO revenue growth is set back due to the uncertain economic outlook and MNOs' focus turns more to cost reduction than maximising demand growth. The decline in linear TV is much slower than expected as SVoD struggles to recapture past levels of growth also due to the uncertain economic outlook. However, the DTT platform does still evolve through investment made primarily in video coding upgrades by the owners of the DTT platform for delivery of more HDTV content. PMSE demand continues to grow moderately.

In this scenario, there are no changes to how the 470-694 MHz UHF spectrum is allocated from the early 2030s. The UHF spectrum range remains allocated to broadcast services on a primary basis and land mobile allocated on a secondary basis as per the current Ofcom Frequency Allocation Table, where PMSE continues to use interleaved DTT spectrum. The Exhibit below depicts the spectrum allocations in this range including the existing UK mobile operator allocations up to 862 MHz for reference, which is up to where broadcast originally occupied prior to the first Digital Dividend afforded by the switch-off of analogue TV in the early 2010s.

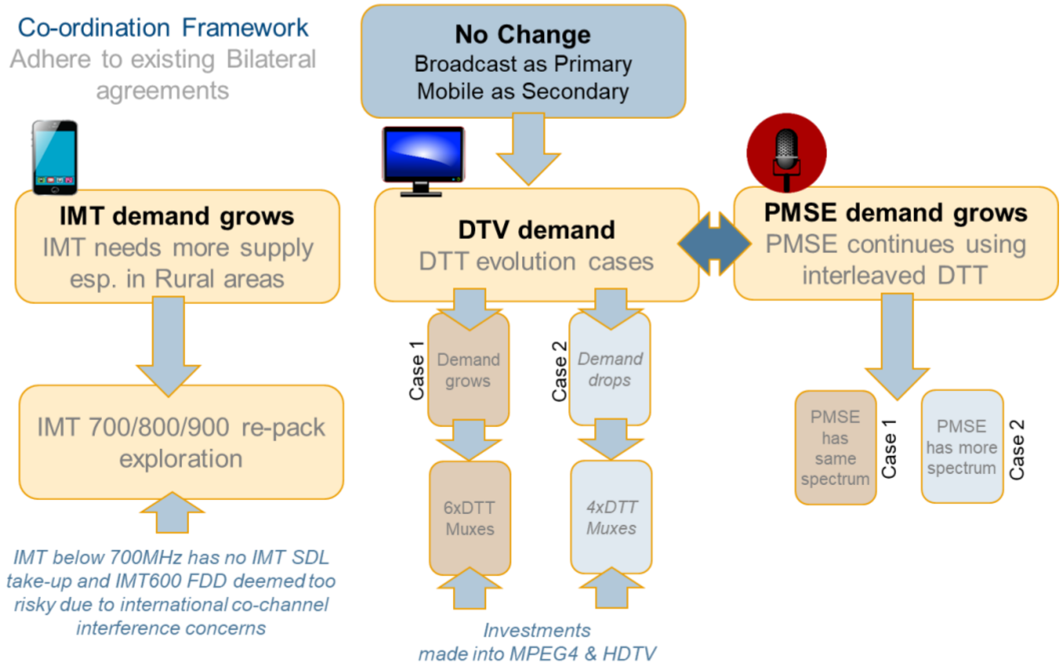
Exhibit 9: No-change to spectrum allocations scenario – spectrum allocation for DTT, IMT & PMSE



Source: Coleago Consulting

There can be several cases under this "no change to 470-694 MHz" scenario as to how DTT as the primary allocation in the 470-694 MHz band could evolve. We present two possible evolutionary cases linked to how DTT might evolve. These DTT evolution cases are illustrated in the Exhibit below and described in more detail in the following paragraphs.

Exhibit 10: No-change to spectrum allocations scenario - evolution cases between DTT, IMT & PMSE



Source: Coleago Consulting

The "no change to 470-694 MHz" scenario for the UK may be brought about or influenced strongly by the interference concerns from high power DTT transmissions in neighbouring countries such as France or the Republic of Ireland being co-channel with the uplink sub-band of FDD based IMT600 networks in the UK. This co-channel interference mechanism is often cited by many industry stakeholders as the principal barrier for supporting co-primary broadcast and mobile allocation of the band where mobile has an uplink channel, because coordination distances of over 200km or greater have been shown to be ideally needed[45]. These co-channel interference risks are examined further, along with mitigation considerations in Section 4.3.2 when the scenario where an IMT600 FDD band plan in the UK is considered.

The "no change to 470-694 MHz" scenario for the UK may also be brought about or influenced by a lack of adoption of 3GPP specified supplemental downlink (SDL) band plans and channel arrangements by 2030. Such IMT SDL band plans have been proposed to allow a more harmonious co-primary broadcast and mobile co-existence in the UHF band. IMT SDL for the UHF band proposes 8 MHz channel sizes for LTE & 5G in order to fit into the existing UHF channel sizes. The introduction of IMT SDL is examined in the next scenario in Section 4.2.3.

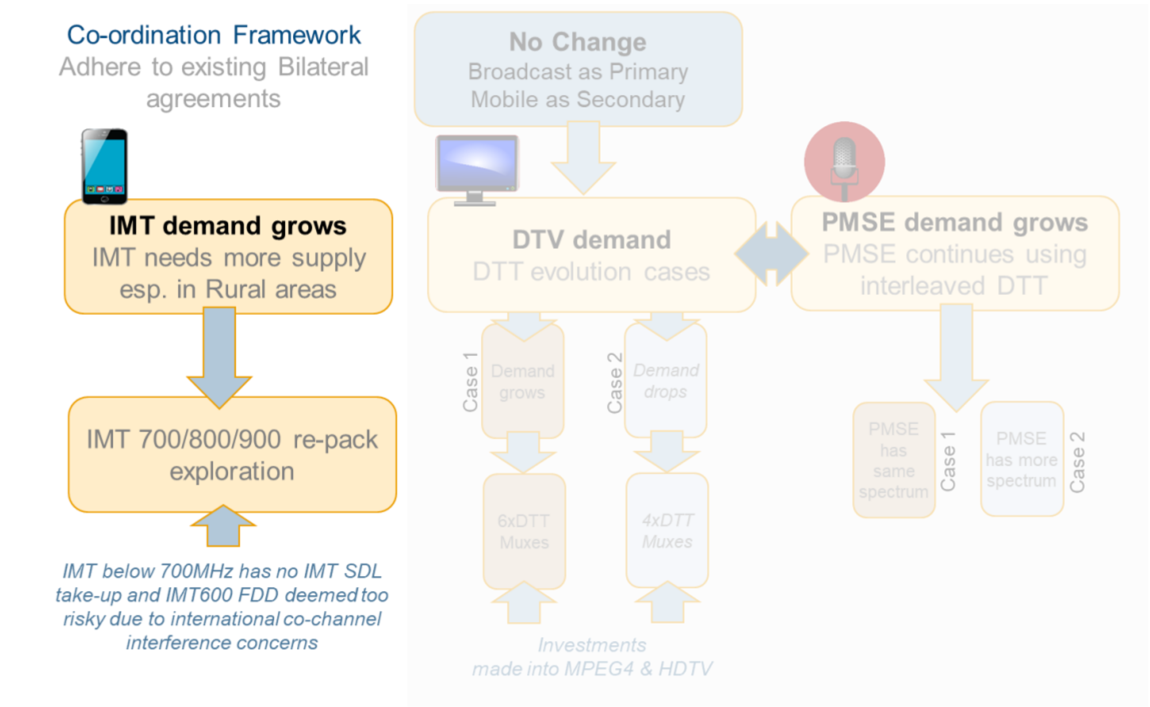
4.1.1 IMT under "no change"– all cases

In this "no change to 470-694 MHz" scenario, there would be no additional low-band spectrum resources available for the mobile operators to help meet their growing traffic needs, regardless of how DTT evolves and hence applies to all cases under this scenario. Since the first Digital Dividend, over the last decade, mobile operators have deployed 4G services which includes 800 MHz band. According to Ofcom's Connected Nations 2021 report[46], over 96% of premises in rural areas across the UK now have access to 4G services indoors. During the rest of this decade we can expect to see operators deploy 5G services, and more 4G capacity using 700 MHz and using re-farmed 900 MHz spectrum as 3G and eventually 2G services are shut down in the 900 MHz band. Assuming the continued growth in traffic demand, and no additional low-band IMT spectrum the mobile industry may need to explore more ways of increasing spectral efficiencies from their existing low-band spectrum for the 2030s. One area for exploration is whether there could be spectral efficiency gains achieved through defragmenting and repacking operator spectrum allocations across the 700, 800 and 900 MHz bands.

[45] https://www.itu.int/pub/R-REP-BT.2337

[46] https://www.ofcom.org.uk/research-and-data/multi-sector-research/infrastructure-research/connected-nations-2021/interactive-report

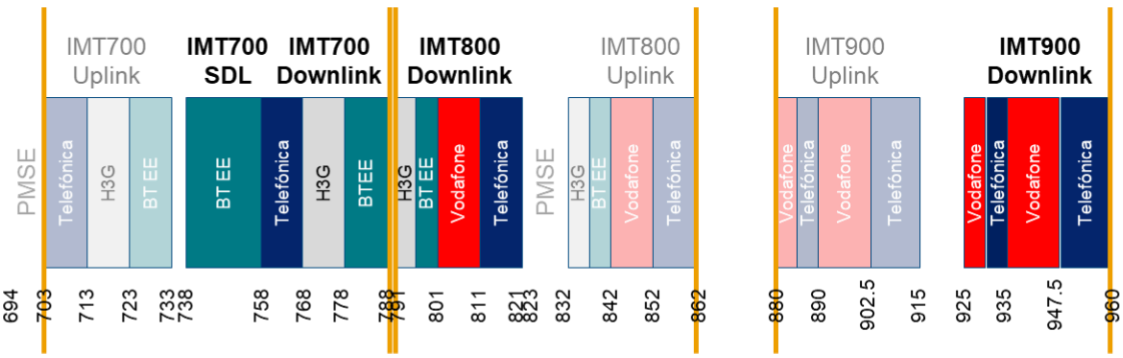
Exhibit 11: No-change to spectrum allocations scenario - evolution for IMT



Source: ColeagoConsulting

The Exhibit below illustrates the current low-band spectrum allocations in the 694-960 MHz range in the UK for the UK MNOs. These allocations are the result of spectrum auctions at 800 MHz and at 700 MHz, plus some recent rationalisation in the 900 MHz band which Telefónica O2 and Vodafone have always occupied. An analysis of these operator spectrum allocations does indicate a couple of inherent spectral inefficiencies brought about by the fragmented allocations.

Exhibit 12: MNO spectrum allocation across 700, 800, and 900 MHz bands



Source: Coleago Consulting

All operators have allocations which are across at least two bands. This is not seen as a network capacity inefficiency as such since the same total number of LTE or 5G resource blocks are available. The same inherent capacity is provided by two 5 MHz channels as one 10 MHz channel. A first perceived inefficiency in using allocations from different spectrum bands is having to rely on carrier aggregation device support to exploit and experience higher throughput rates. Consider the scenario where devices are at the cell edges and only have access to low-band spectrum. There are very few IMT devices supporting carrier aggregation combinations across these 700, 800, and 900 MHz bands at present, as most carrier aggregation support is focused on low-band plus mid-band combinations for increasing throughputs. There are also associated additional signalling overheads in managing carrier aggregation normally manifesting as some latency increases. However, if by the early 2030s, there might be a large and growing population of devices supporting carrier aggregation across these bands, there would be a diminishing impact in throughput experiences at the cell edges in having fragmented versus non-fragmented spectrum allocations. This however is an area we recommend for proposed further investigation.

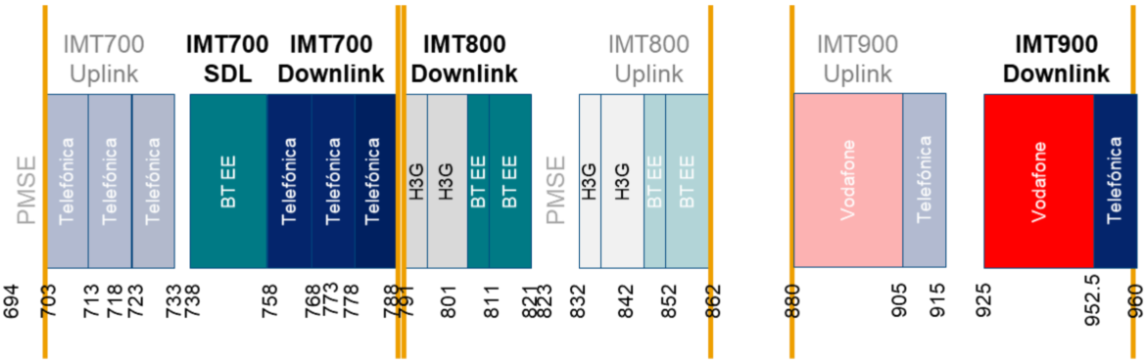
A second spectral inefficiency is related to some of the specific operator band combinations leading to some Passive Intermodulation (PIM) interference risks. It is beyond the scope of this study to detail these, but to avoid PIM interference, it is common to use two separate RF chains and antenna arrays to host the fragmented spectrum. This means there would be less opportunity to take advantage of higher order MIMO configurations, such as 4 x 2 MIMO on downlink, in one or more bands at a future date, since additional antenna arrays needed to support higher order MIMO are being used for PIM interference avoidance. 4 x 4 MIMO at low-band for handheld devices is generally not possible due to size limitations of handheld devices not being able to accommodate four antennas. However, larger devices and connected vehicles could take advantage of 4 x 4 MIMO, and multiple handheld devices may also be scheduled using 4 x 4 multi-user MIMO (MU-MIMO) schemes for capacity enhancements too. A full discussion of MIMO schemes however is beyond the scope of this project.

Band defragmentation in principle may solve these inefficiencies, but because 700 MHz (Band 28) is a more recent band globally, there are generally fewer devices which support 700 MHz than 800 MHz band currently. The August 2022 GSA LTE Ecosystem report indicates that there are just over half as many devices supporting 700 MHz than for 800 MHz as of August 2022[47]. This implies that spectrum at 800 MHz, at this time at least, may be seen as being more valuable to an operator than 700 MHz band, simply because there will be more subscribers able to access 800 MHz than 700 MHz.

700 MHz spectrum however continues to be allocated, and 700 MHz networks continues to be deployed around the world, most notably Jio in India recently securing 700 MHz[48], and China Broadcast Networks announcing their deployment at 700 MHz[49]. In several years' time (perhaps around 2030) we could expect similar levels of LTE and 5G device support across all three spectrum bands at 700, 800 and 900 MHz. At such a time, the value of 700 MHz and 800 MHz spectrum to each operator may become more blurred. Likewise, the value of 900 MHz spectrum to Telefónica and Vodafone may be seen as being similar to 700 or 800 MHz.

Therefore, from 2030 there may be more desire and appetite for operators to engage in a spectrum defragmentation process across the 700, 800 and 900 MHz bands. It does not make sense for defragmentation now. There are also dozens of potential defragmentation outcomes, and these will also be influenced by operator sharing agreements such as those in place with Vodafone and Telefonica, and any future operator consolidation. The Exhibit below depicts an example outcome of a future low-band spectrum defragmentation process perhaps achieved via spectrum trading mechanisms. In this example, all operators achieve more contiguous spectrum in a single band (except for Telefónica in the example) thereby reducing reliance on carrier aggregation and maximising cell edge throughput experiences when Low-Band spectrum might only be available (e.g., at the cell edges).

Exhibit 13: Example defragmented MNO spectrum allocation across 700, 800, and 900 MHz bands



Source: Coleago Consulting

The above spectrum configuration is designed to also minimise PIM interference, such that the need for maintaining separate RF/Antenna chains is avoided, and thus maximise the opportunity for operators to use higher order MIMO at

47 LTE Ecosystem August 2022: Quarterly update, GSA

48 https://www.lightreading.com/asia/does-jios-gamble-on-700mhz-give-it-advantage-over-airtel-/d/d-id/779510

49 https://www.mobileworldlive.com/asia/asia-news/cbn-china-mobile-settle-700mhz-5g-plan

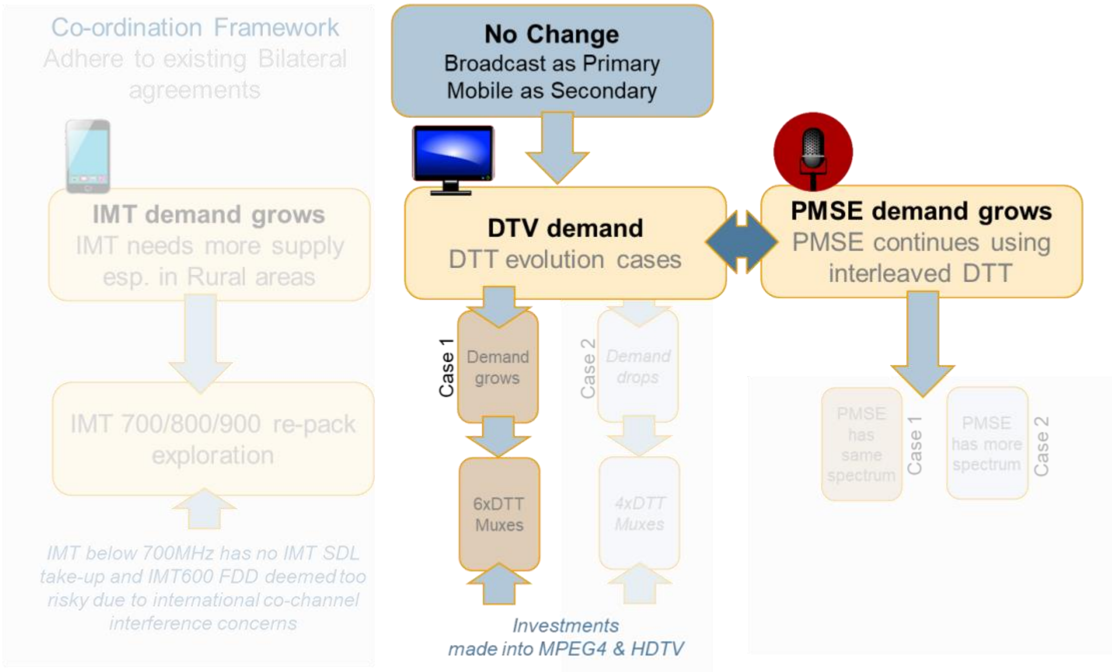
low-band through in using 4T4R radio configurations to deliver downlink 4 x 2 (or even 4 x 4 MIMO to devices capable of supporting 4x terminal antennas). We estimate that the defragmentation of spectrum in this manner could provide between 20-40% capacity gains[50]. There could also be a useful increase in downlink coverage owing to precoder based beamforming gains in using a dual cross-polar antenna arrays, which would be valuable for further enhancing rural area coverage and for increasing in-building penetration.

Such defragmentation may however benefit one operator more than another, which we would expect to be reflected in any spectrum trading prices, though it may also create competitive imbalances. Additionally, operators may have already factored such inefficiency and competitive aspects into their network roadmaps. As such there is also the real possibility that spectrum does not get defragmented due to competitive tension and ultimately remains with some inefficiencies.

Studies on re-farming the entire 694-960 MHz band to arrive at completely new band plans have been proposed and studied[51]. These new band plans essentially explore the capacity gains if the current 700, 800 and 900 MHz band plans could be consolidated, removing guard-bands and reducing duplex gaps, and even includes a conversion of the whole band to TDD. The practical challenge is how such new bands could ever be introduced, as it would require global efforts, and a lengthy transitional period which may have to endure lower spectral efficiencies in the band before reaping the greater spectral efficiencies of any new band plan across 694-960 MHz. As such, we do not consider these as practical options for a 2030 timeframe at least.

4.1.2 No change– Case 1: DTT grows

Exhibit 14: No-change to spectrum allocations scenario - evolution for DTT – case 1



Source: Coleago Consulting

[50] https://www.5gamericas.org/wp-content/uploads/2019/07/2018_5G_Americas_Rysavy_LTE_to_5G-_The_Global_Impact_of_Wireless_Innovation_final.pdf

[51] The defragmentation dividend, A more efficient use of the UHF band White paper on behalf of Digital UK, Nov 2017

4.1.3 DTT under no change– case 1: DTT grows

As stated earlier there are several cases as to how DTT could evolve from today's network until the early 2030s. We examine two possible cases. The first case examined is where there is an increase in the HDTV payload of DTT programmes brought about by some investments in the DTT platform.

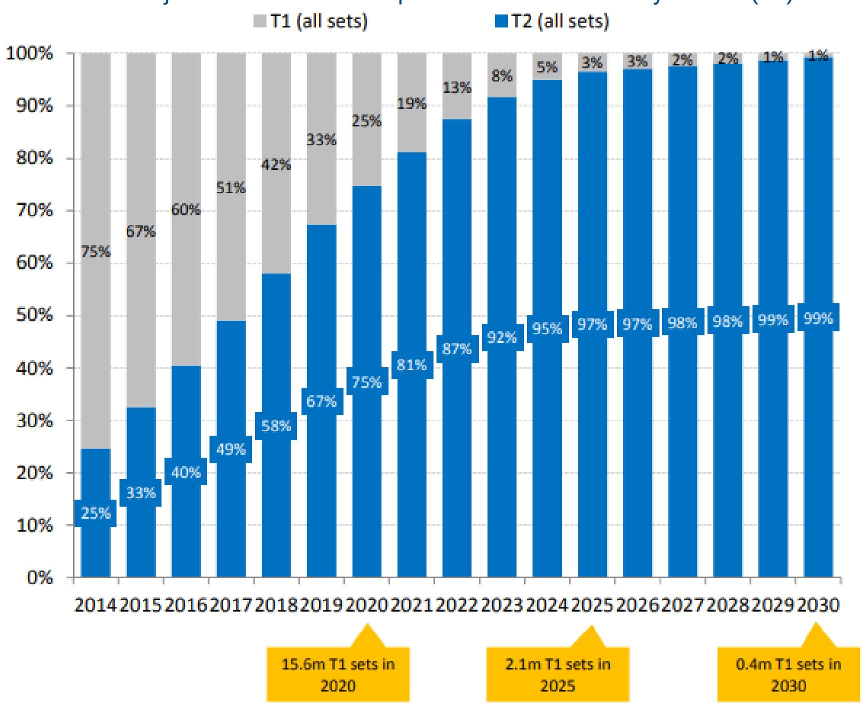
All SDTV programmes on the five DVB-T multiplexes are currently encoded using MPEG2 video coding. The UK is one of the few countries in Europe to continue to use MPEG2 coding for SDTV content at a national level. For what should be a modest investment into the DTT network (but subject to further study) all current SDTV content carried on the five DVB-T multiplexes could be encoded using H.264 or Advanced Video Coding (AVC) with an MPEG4 transport.

Assuming that almost all TV receivers are also AVC/H.264 MPEG4 compatible by early 2030s virtually all TV households should be able to take advantage of AVC/H.264 MPEG4 video coding. Also, it is fully expected that all AVC/H.264 MPEG4 patent licencing will have expired after 2030, meaning that any ongoing costs for encoding content for delivery via the DTT network should be minimised. AVC/H.264 MPEG4 coding allows approximately a 50% decrease in bit rate to support the same picture quality as MPEG2 coding. Such a move to AVC/H.264 MPEG4 coding should comfortably allow a meaningful delivery of many more HDTV services.

There are other factors at play which may cause an increase of the opportunity to supply HDTV content. The first factor is associated with TV programme and content makers looking to consolidate programmes delivered by DTT or move certain content away from DTT to online all together as part of cost savings or wider policy objectives, such as the recent decision by the BBC to merge news channels and move BBC Four, CBBC and Radio 4 Extra services away from DTT before 2030[52] . This frees up some DTT capacity for other TV channels to then become HDTV.

Another factor is by the early 2030s, there would not be an expectation or need to provide both simultaneous SDTV and HDTV content of PSB programmes, due to the almost universal proportion of TV sets capable of supporting H.264/MPEG4 and HDTV by that time, and thus allows DTT capacity to be released for enabling other HDTV for other programmes. However, the key enabling factor for more HDTV content would be the investment into the DTT platform for supporting at least H.264/MPEG 4 video coding and possibly upgrading to more DVB-T2 multiplexes. A study carried out by Mediatique in relation to an Ofcom consultation predicted that by 2030 there would be fewer than 0.4m households relying solely on DVB-T[53] This graph serves as a proxy for HDTV penetration since all DVB-T2 receivers support H.264/MPEG 4.

Exhibit 15: Projected % households' penetration of TV sets by DVB-T (T1) & DVB-T2 (T2) technology in the UK



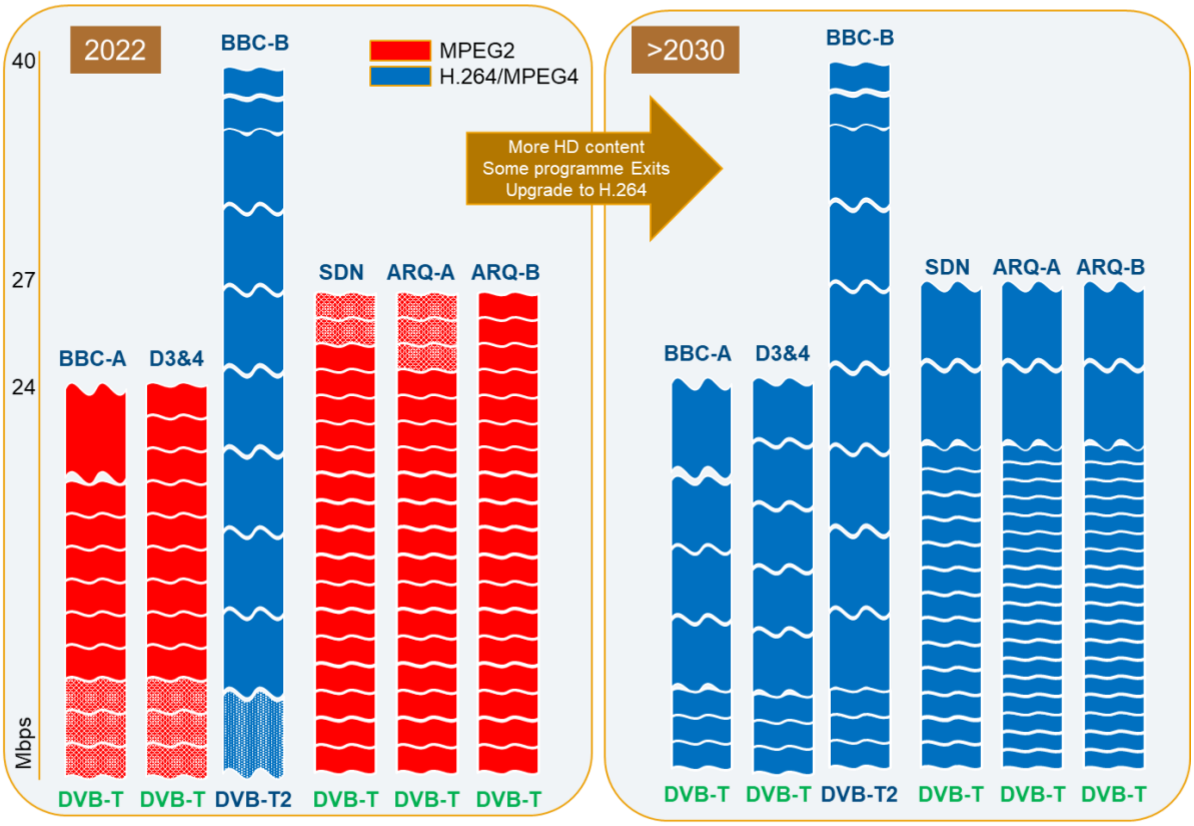
Source: Mediatique

[52] https://rxtvinfo.com/2022/multiple-bbc-channels-to-close

[53] https://www.ofcom.org.uk/data/assets/pdf_file/0024/40569/mediatique.pdf

Due to these factors, it may be conceivable by the early 2030s the DTT network could deliver much more HDTV programme content using its six multiplexes. The concept of such a DTT upgrade is illustrated below to provide more HD content, maintaining some SD content, along with some policy driven TV channel departures, and removal of dual SD/HD content delivery by the early 2030s. In the illustration below we have assumed that video coding is upgraded only, but equally multiplexes can also be upgraded to DVB-T2 to support more capacity. The exact upgrade route will depend upon the amount of HDTV content envisaged, and the business case for such investments.

Exhibit 16: No change to spectrum allocations scenario – example of the evolution for DTT m- case 1



Source: Coleago Consulting

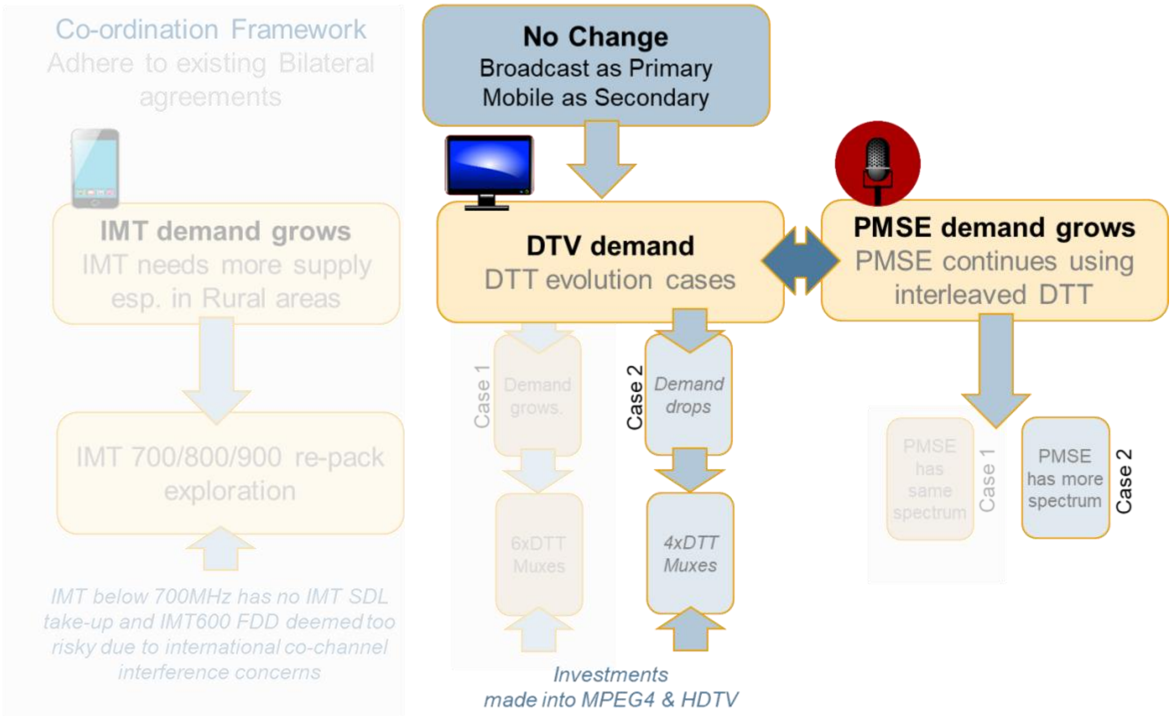
4.1.4 PMSE under no change– case 1: DTT grows

In the event DTT HDTV content increases via investment into the DTT network, and all six multiplexes are maintained under this “no change to 470-694 MHz” scenario, there would be correspondingly no more or no less interleaved spectrum available for PMSE use.

Empirical evidence reveals there are cases that professional audio PMSE spectrum demand is slowly increasing largely driven by increasingly large and more frequent media and arts events (such as Glastonbury, Eurovision, etc.). Such increases in PMSE peak demand during the 2030s, may be addressed through emerging PMSE technologies such as WMAS. If, however, WMAS is not adopted at meaningful levels to absorb such peaks in professional PMSE, then the PMSE community may need additional PMSE spectrum bands, and/or make more use of the existing 960-1164 MHz aeronautical band.

4.1.5 DTT under no change– case 2: DTT declines

Exhibit 17: No change to spectrum allocations scenario - evolution for DTT – case 2

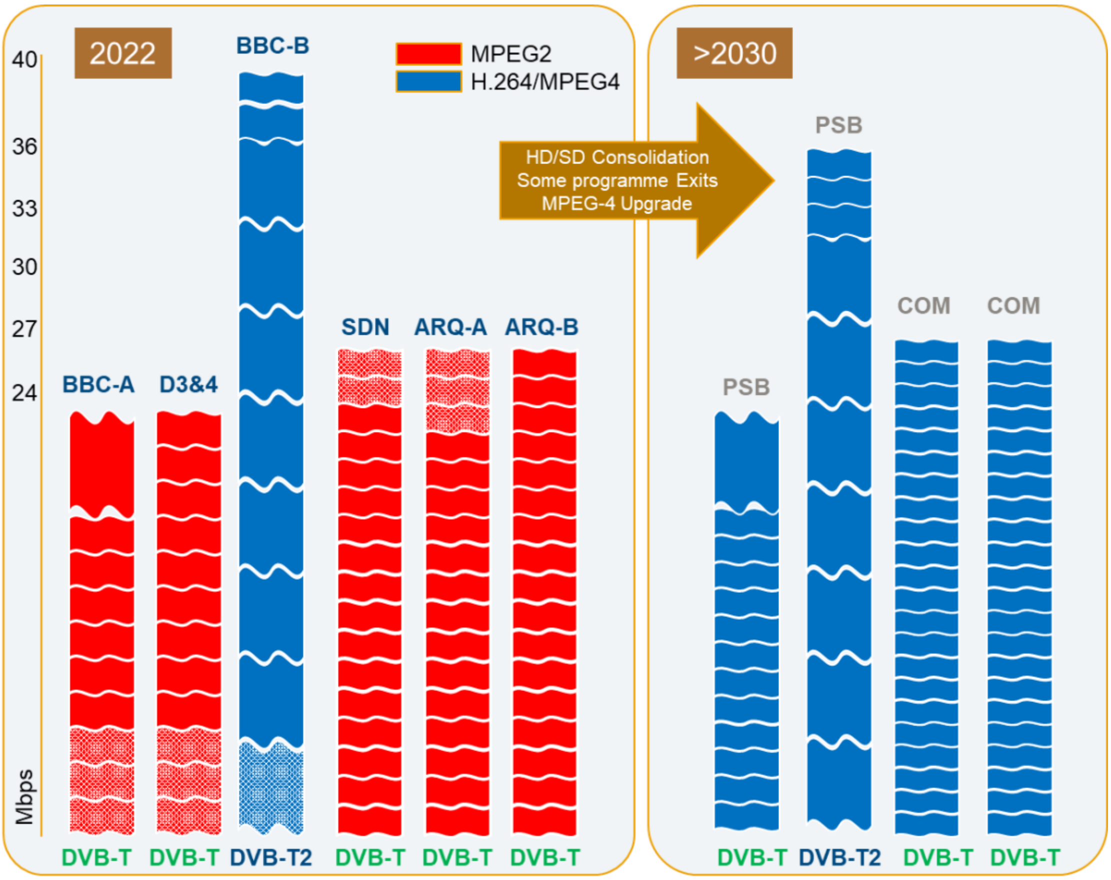


Source: Coleago Consulting

In this case there is network investment made into upgrading the network with H.264/MPEG4 video coding as per the previous case to offer more HDTV content, but there are more departures than expected and muted demand for such HDTV services. This decline would include the already planned departures of some TV programmes and consolidation of parallel HD/SD content delivery as described for the previous case.

Such a move to H.264 MPEG4 coding coupled with a lack of HDTV demand may allow for a consolidation from today's five DVB-T multiplexes to three or four DVB-T multiplexes to at least continue to support today's TV programme payload. The concept of consolidation through some decline and AVC/H.264 MPEG4 upgrading is illustrated in the Exhibit below. The precise ownership or part ownership of the consolidated multiplexes would be subject to further study and assessment for such a case.

Exhibit 18: No change to spectrum allocations scenario – example of the evolution for DTT in case 2



Source: ColeagoConsulting

4.1.6 PMSE under no change– case 2: DTT declines

In the event DTT supply is maintained under a "no change to 470-694 MHz" scenario, by additionally using AVC/H.264 MPEG4 coding upgrades in the DTT network by 2030, then there would be on average 16 MHz more interleaved spectrum available for PMSE use. The DTT multiplexes have reduced, from today's six multiplexes to four multiplexes by the early 2030s, releasing this spectrum dividend for PMSE. In many respects, this spectrum dividend, through the use more up to date video coding for the DTT network, could be viewed on one level as giving some of the PMSE spectrum back which it effectively lost during the IMT700 band clearance.

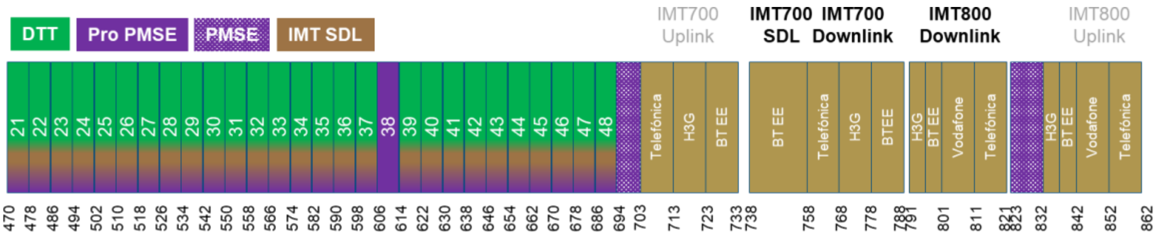
Empirical evidence reveals there are cases that professional audio PMSE spectrum demand is slowly increasing largely driven by increasingly large and more frequent media and arts events (such as Glastonbury, Eurovision, etc.). The additional interleaved spectrum freed up by the DTT network should provide some balance and satisfy such PMSE demand increases during the 2030s. If this reduction in TV demand can meet the increase in PMSE there may not be such a pressing need for the PMSE community to continually search for new spectrum bands to cater for their peak spectrum demands or have to rely on more expensive PMSE equipment and PMSE spectrum management efforts.

4.2 Flexible use - co-primary broadcast & mobile services

Our indicative set of key trends for this scenario is as follows. Mobile data demand continues to grow at a similar level to the previous five years and rural areas experience congestion. Linear TV declines steadily, but the number of DTT households falls more slowly limiting UK broadcasters' appetite for significant investment in more spectrally efficient DTT technology. However, internationally, there is significant support for 5G Broadcast driven by its ability to increase revenues as a complement to traditional broadcasting and not as a radical alternative to DTT. PMSE demand continues to grow moderately.

In this scenario, a co-primary allocation for broadcast and mobile services is in force for the entire 470-694 MHz range from the early 2030s. This scenario reflects the regulatory framework which promotes the idea for different countries (especially in a European context) to adopt a more co-operative and flexible regulatory environment for DTT, DTT & IMT, or IMT in the band, to better suit each country's different needs and timing of for these services. This co-primary scenario would assume that any IMT services which are deployed in the band are Supplemental Downlink (SDL) of 8 MHz channelisation and not FDD or TDD. The Exhibit below depicts the spectrum allocations in this range including the existing UK mobile operator allocations up to 862 MHz for reference.

Exhibit 19: Co-primary use for 470-694 MHz scenario – spectrum allocation for DTT, IMT & PMSE



Source: Coleago Consulting

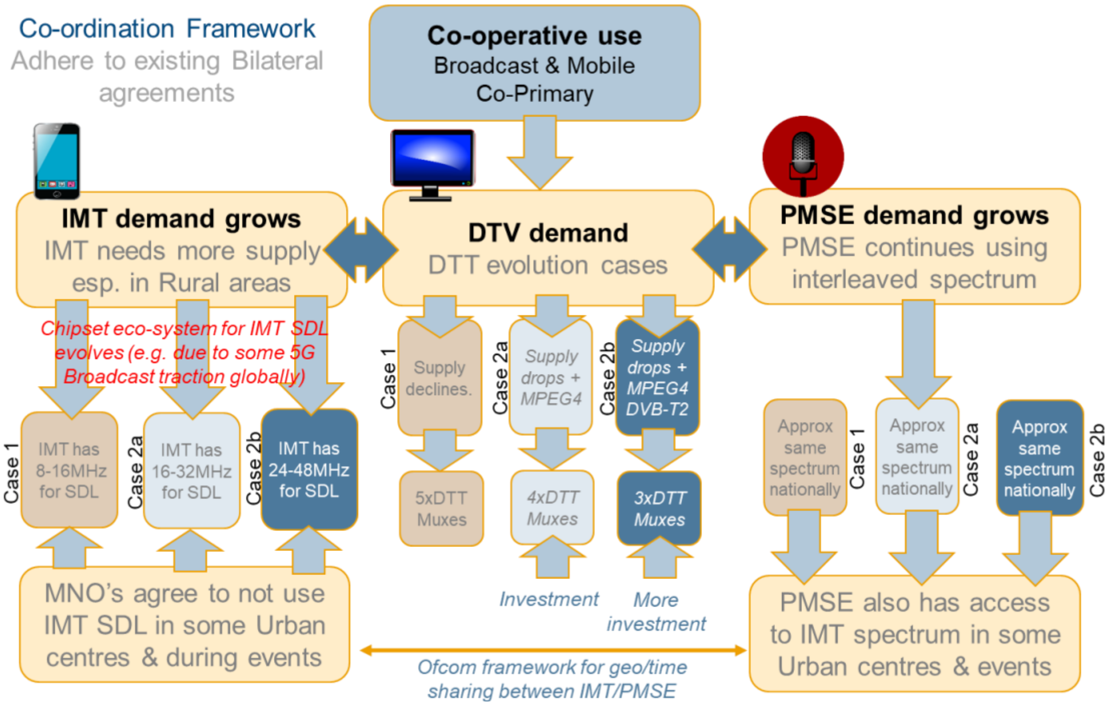
As highlighted with the "no change to 470-694 MHz" scenario, this "co-primary use for 470-694 MHz" scenario for the UK may be brought about or influenced strongly by the interference concerns from high power DTT Transmissions in neighbouring countries such as France or the Republic of Ireland being co-channel with the uplink sub-band of FDD based IMT600 networks in the UK. This co-channel interference mechanism is often cited by many industry stakeholders as the principal barrier for supporting co-primary broadcast and mobile allocation of the band where mobile has an uplink channel, because coordination distances of over 200km have been shown to be ideally needed. These co-channel interference risks are examined further, along with mitigation considerations in Section 4.3.2 when the scenario where an IMT600 FDD band plan in the UK is examined.

IMT as an SDL using 8MHz channels service permits a more harmonised spectrum environment between DTT and IMT especially between neighbouring countries who may wish to use DTT and IMT differently in the band. The spectrum arrangement also minimises the need for large area co-ordination across several countries when deploying IMT SDL services.

As with the "no change to 470-694 MHz" scenario there are different evolutionary cases which could emerge under this "co-primary use for 470-694 MHz" scenario. We present two possible evolutionary cases linked to how DTT evolves, where the second of these cases examines two different levels of potential investment into the DTT network. These DTT evolution cases are illustrated in the Exhibit below and described in more detail in the following paragraphs.

Please note - we do not show a case where investment is made into the DTT network for increasing HDTV services and thereby maintaining six multiplexes, as we did for the previous scenario. If DTT remained with six multiplexes, we would not see a case for IMT SDL at all. This is because under this situation IMT SDL could only ever use interleaved DTT spectrum, and effectively becomes a TV white space application, and would have a highly variable quantity of white space spectrum availability as a function of location, making such IMT SDL unattractive. Furthermore, IMT SDL would directly compete against PMSE for spectrum, and both services would have equal priority being primary services. As such, we only consider the cases where there would be a reduction in TV demand, thereby allowing for the opportunity for spectrum dividend to be used for IMT and PMSE use.

Exhibit 20: Co-primary use for 470-694 MHz scenario - evolution cases for DTT, IMT & PMSE



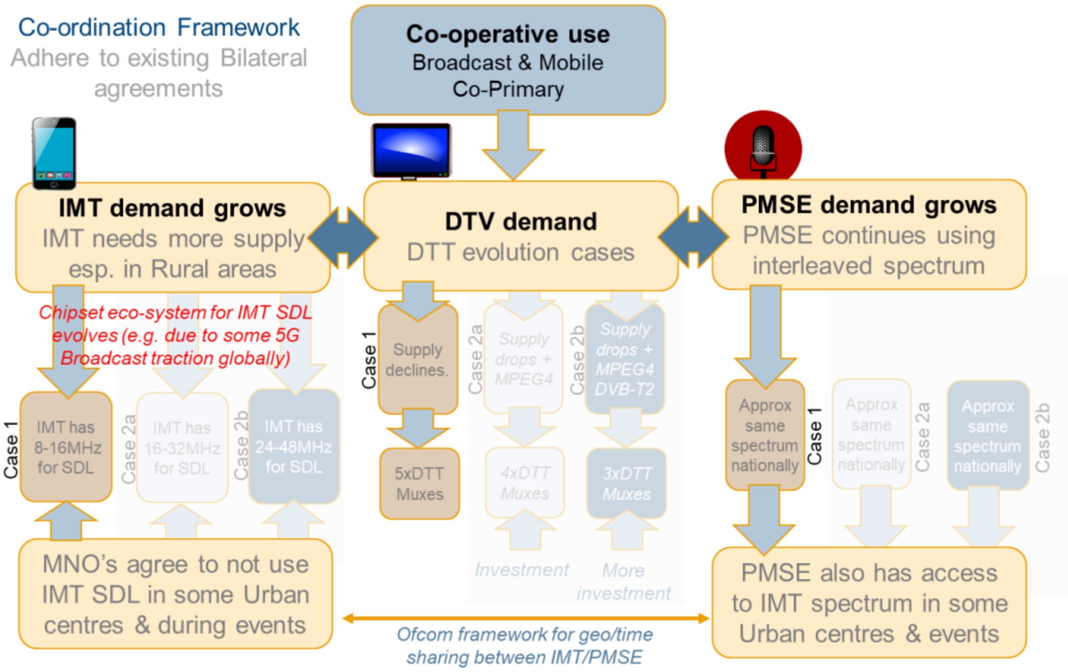
Source: Coleago Consulting

It is worth stressing however that the possibility for this scenario is highly dependent upon the successful emergence of an IMT device eco-system sometime after 2030 which is based on standardised IMT band plans and channel arrangements. Currently, there are no 3GPP band plans for IMT SDL in the 470-694 MHz range under consideration. It is also worth noting that for this case to become a possibility, there strictly would not need to be a co-primary allocation agreed at WRC-23. The current European UHF decision allows for flexible use so long as DTT isn't interfered with. However, a co-primary decision would additionally allow for protection to IMT and for that matter PMSE users.

One route in arriving at an IMT SDL device eco-system for this 470-694 MHz band may be via the adoption of 5G Broadcast networks in meaningful numbers at least in a region or a large market which can drive adoption such as China or India. 5G Broadcast is currently standardised in 3GPP Release 16 and there is ongoing work to define channel bandwidths of 6, 7 and 8 MHz designed to fit into UHF TV channel bandwidths. If 5G Broadcast networks are deployed in sufficient quantities then chipset support for IMT devices will follow, since 5G Broadcast is designed for consumption by mobile devices. Once device chipset support for 5G Broadcast is achieved, the transition to IMT SDL can be much easier since UHF band plans and 8 MHz channelisation will have been established. IMT SDL emergence does not have to rely on 5G Broadcast being successful, but it may help it to gain traction.

4.2.1 Co-primary– case 1: DTT declines & IMT SDL used

Exhibit 21: Co-primary use for 470-694 MHz scenario - evolution case 1



Source: Coleago Consulting

4.2.2 DTT under co-primary– case 1: DTT declines & IMT SDL used

As also discussed for the “no change to 470-694 MHz” scenario, there are factors at play which may cause a reduction of the supply of TV capacity of the DTT network:

- The decline in any demand/viewing of broadcast linear TV content resulting in policy changes by content providers to consolidate and/or take content away from DTT to online, such as the recent BBC decisions for BBC Four, CBBC and Radio 4 Extra to be taken away from DTT;
- Installed DTT capacity reduction due to almost universal DVB-T2/MPEG4 receiver penetration by 2030 with less need for parallel delivery of HD and SD content by 2030; and
- Lack of demand or reduced business case for delivering additional DTT HDTV services.

Assuming also that there is no investment into the DTT network in terms of MPEG4 also, then it may be conceivable by the early 2030s the DTT network can deliver its content using around five multiplexes in total, where one multiplex remains as a DVB-T2 multiplex. This reduction in DTT spectrum provides the basis for a spectrum dividend for providing the IMT SDL spectrum in this first case.

Whilst it may be argued that it is technically possible to deliver a reduced supply in fewer multiplexes if there is a decline in DTT demand, the DTT network would however require some re-engineering to ensure PSB coverage levels are met and repacking of TV programmes into the remaining five multiplexes. This raises questions as to how DTT network re-engineering would be funded, as Arqiva as a commercial entity, would not be necessarily obliged to do this unless there was an incentive or funding. This would be an area recommended for further investigation and study.

This case where there is a small reduction in installed DTT capacity (in the no. of multiplexes) to provide a spectrum dividend could also occur under a “No change” scenario. However, in having a co-primary regulatory framework as per this scenario is more likely to encourage Mobile Operators to consume any dividend spectrum. The “No change” to regulation scenario means IMT in 470-694MHz remains secondary, and less likely that Mobile Operators to consume any potential dividend spectrum.

4.2.3 IMT under co-primary– case 1: DTT declines & IMT SDL used

In this first case of “co-primary use for 470-694 MHz” scenario, where the DTT supply declines and remaining TV programmes can be re-packed into a smaller number of multiplexes, there would be a small spectrum dividend available for IMT SDL use. The DTT network reduces from six to five multiplexes meaning at least 8 MHz becomes available for IMT SDL use in all locations. In areas where there is overlap from two main DTT broadcast transmitters there can be up to two 8 MHz channels available for IMT SDL. As such there would be a variable amount of spectrum available for IMT SDL use across the UK, of at least 8 MHz and in many locations 16 MHz. The extent of availability of 16 MHz of IMT SDL spectrum would have to be determined through further study.

The quantity of 8-16 MHz of IMT SDL spectrum maybe considered sufficient for one MNO but likely insufficient to satisfy the needs of all UK MNOs. If decline in TV demand may be more pronounced over the coming years this could lead to an opportunity to repack content into even fewer multiplexes, thus releasing more IMT SDL spectrum, although this more aggressive decline is more speculative.

Any UHF channels which could be vacated by DTT are well suited for IMT SDL, as these channel arrangements can also largely continue to adhere to any existing bilateral spectrum coordination agreements between France, the Republic of Ireland, the Netherlands and Belgium. However, MNO sites with IMT SDL which are located towards the edges of the service areas of the main DTT broadcast transmitters, and which also fall into the international coordination zones (e.g., SE England, Wales, Northern Ireland) may need some coordination effort with neighbouring countries.

Given the lower power and lower heights of IMT SDL deployments compared to main broadcast DTT sites (which coordination is normally based upon), there should be relatively low risks of increased interference to France, Ireland, the Netherlands and Belgium from UK IMT SDL deployments. International coordination does however factor in Polarisation discrimination between DTT areas, and as such there may be a need to adopt space diversity V-Polarized (or H-Polarized) IMT SDL base station antennas rather than Cross-Polarized antennas for some areas which might be more exposed to possible interference from IMT. This is an area for further study in the event IMT SDL might be used.

It would also be possible for MNOs to consume more spectrum beyond that released by any DTT multiplex consolidation process. It would be possible for example for IMT SDL to use white space or interleaved spectrum between the main DTT broadcast sites, much in the same way PMSE uses interleaved spectrum. The available quantity of interleaved spectrum as a function of location will be highly variable too. This IMT SDL approach in using interleaved spectrum would however directly impact spectrum normally available for PMSE. It may be possible for PMSE and IMT SDL to both share interleaved spectrum, but this is expected to need detailed coordination effort. The idea of MNOs not deploying IMT SDL in certain locations where PMSE might have high demand, in return for PMSE having access to less interleaved spectrum elsewhere is one idea for further exploration. A version of this idea is presented in Section 4.3.3. This interleaved approach to IMT SDL may be something that should be considered more fully, especially if there is more certainty as to the emergence of an SDL IMT eco-system for the UHF band.

4.2.4 PMSE under co-primary– case 1: DTT declines & IMT SDL used

In the event DTT supply declines and IMT SDL is adopted in a “co-primary use for 470-694 MHz” scenario, at best there would be no more or no less interleaved spectrum available for PMSE use, since DTT multiplexes have been replaced by IMT SDL allocations.

High demand professional PMSE use is however largely predictable in terms of location and time. High demand is typically observed geographically at for example theatres and large conference venues, and in time at performance arts festivals, touring acts, and at sporting events. It may be possible that for say the largest events and locations across the UK where PMSE is expected to need peak spectrum quantities, that coordination of the IMT SDL spectrum can be managed through a third-party spectrum management function (such as Ofcom or other entity). In this case, the MNO who is assigned IMT SDL spectrum agrees not to activate this IMT SDL spectrum on its sites surrounding the location needing high-demand PMSE spectrum. Such geographic spectrum sharing is examined in Section 4.3.3 when IMT600 FDD is considered.

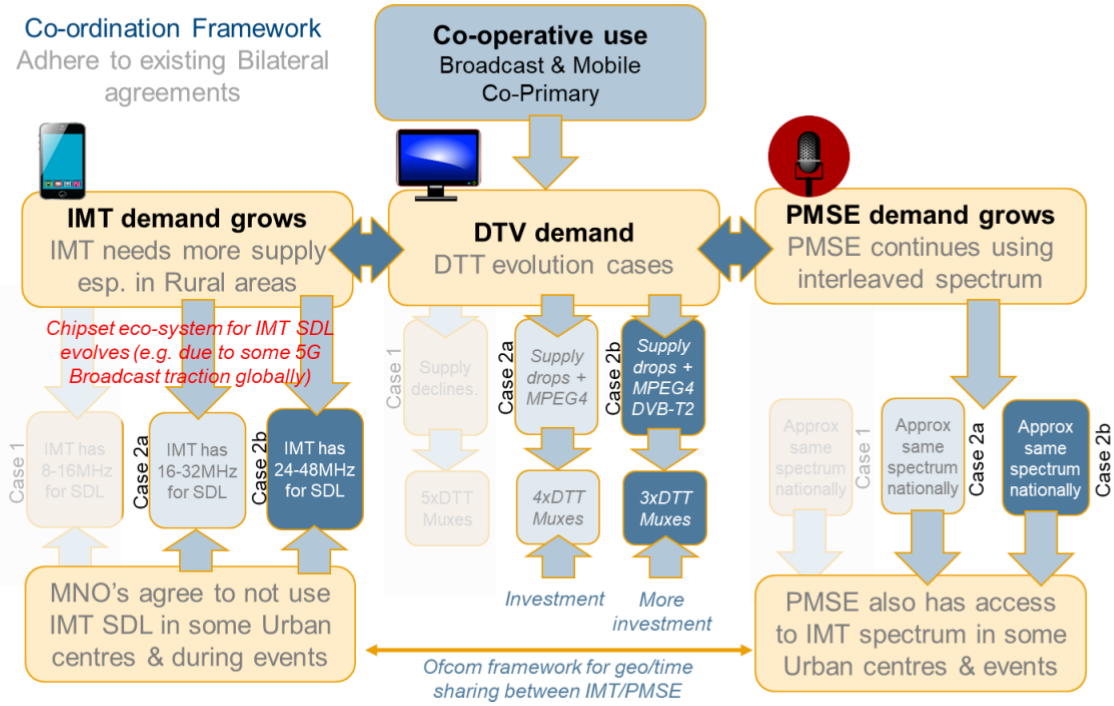
If the IMT SDL spectrum could be licenced in such a manner, then PMSE users on average would observe an increase in available spectrum for professional PMSE where and when professional PMSE is needed most.

4.2.5 Co-primary– case 2: invest in DTT for IMT SDL

The second case is where the UK DTT network experiences some decline in demand for broadcast TV including no or little take up of HDTV services, but also where the DTT platform receives intentional investment to enable a spectrum dividend so IMT SDL spectrum can be created in a meaningful quantity for MNOs. Two cases are examined below, a

Case 2a requiring a modest investment, and a Case 2b with a more substantial investment (both cases subject to studying costs) into the DTT network.

Exhibit 22: Co-primary use for 470-694 MHz scenario - evolution case 2



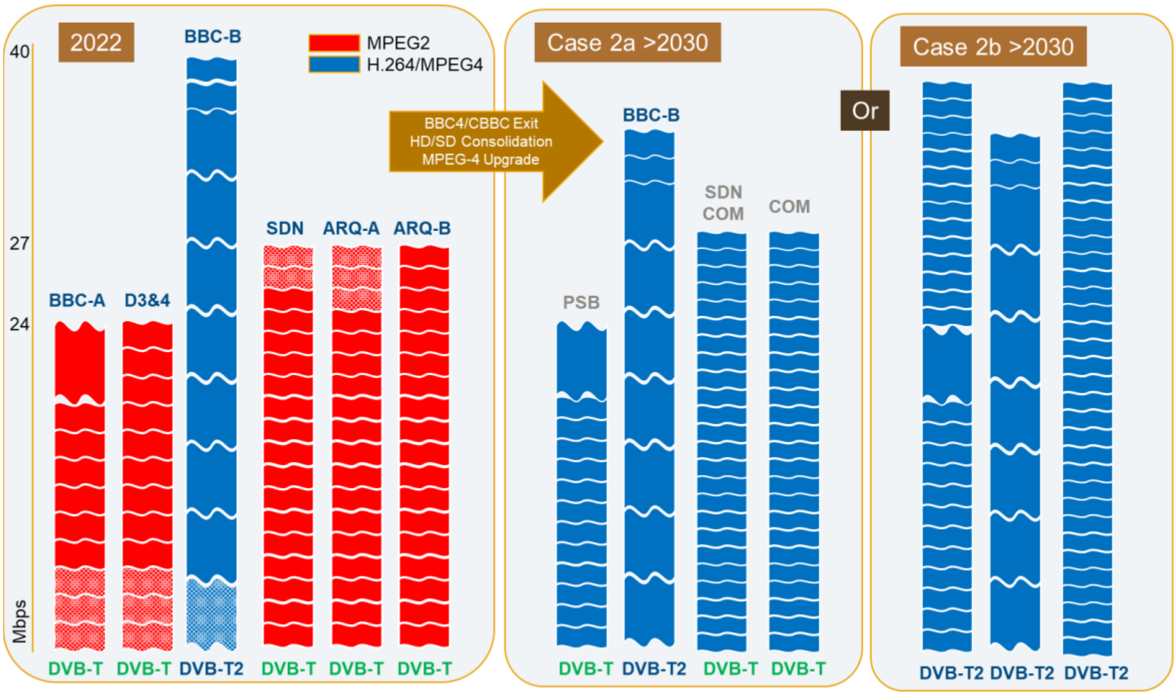
Source: Coleago Consulting

4.2.6 DTT under co-primary– case 2: invest in DTT for IMT SDL

Case 2a is built upon what should be a modest investment (subject to further study) into the DTT network where all SDTV programmes are encoded with H.264/AVC MPEG4 video coding. As stated earlier, the UK is one of the few countries in Europe to continue to use MPEG2 for SDTV content at a national level. Given that all DVB-T2 receivers are also at least H.264/AVC MPEG4 compatible, then by 2030 virtually all TV receivers can take advantage of H.264/AVC MPEG4 coding. By 2030, H.264/AVC MPEG4 patent licencing obligations will have expired too meaning that any ongoing costs for encoding content for delivery via the DTT network would be negligible. H.264/AVC MPEG4 coding allows approximately a 50% decrease in bit rate to support the same picture quality as MPEG2 coding. If H.264/AVC MPEG4 coding is implemented this should comfortably allow a reduction from today's five DVB-T multiplexes to four DVB-T multiplexes. If parallel delivery HD and SD programmes is also not needed by 2030, along with the expectation that some programmes (e.g., BBC 4/CBBC) move away from DTT, then this may allow multiplex consolidation to three DVB-T multiplexes in total. The DVB-T2 multiplex is maintained but may be adjusted to meet similar coverage levels provided by the PSB DVB-T multiplex (>98.5% households). The concept of consolidation through some decline and AVC/H.264 MPEG4 upgrading is illustrated in the Exhibit below.

Case 2b proposes a higher level of investment into the DTT network, where an upgrade to all DVB-T multiplexes is made to DVB-T2 by 2030, in addition to the H.264/AVC MPEG4 coding upgrades. Such a DVB-T2 upgrade would allow a valuable increase in capacity per multiplex. The two DVB-T PSB multiplex currently carry payloads of 24Mbps each (BBC A and D3&4). The three DVB-T commercial multiplex carry payloads of 27Mbps each (SDN, Arqiva 1 and Arqiva 2). The single DVB-T2 multiplex carries a payload of 40Mbps (BBC B) and is approximately equivalent to a DVB-T 27Mbps in terms of C/I or population coverage. As such the two PSB DVB-T multiplexes are designed to provide a little more area coverage than the other multiplexes. It would be reasonable to assume that two DVB-T2 multiplexes (at ~40Mbps each) could support approximately the payload of three DVB-T multiplexes (2x27Mbps plus 24Mbps) with about the same coverage levels. This could mean that the UK DTT platform in principle could be re-engineered from the current six multiplexes to three DVB-T2 multiplexes, implying a reduction in DTT spectrum requirement from 216 MHz to 136 MHz could be possible, assuming similar levels of spectral re-use can be maintained. The Exhibit below illustrates the spectrum dividend concept through video coding upgrades, and DVB-T2 upgrades. The exact upgrade process and design choices are beyond the scope of this study. The precise ownership or part ownership of the consolidated multiplexes would be subject to further study and assessment for such cases.

Exhibit 23: Co-primary use for 470-694 MHz scenario – example of the evolution for DTT multiplexes - case 2



Source: Coleago Consulting

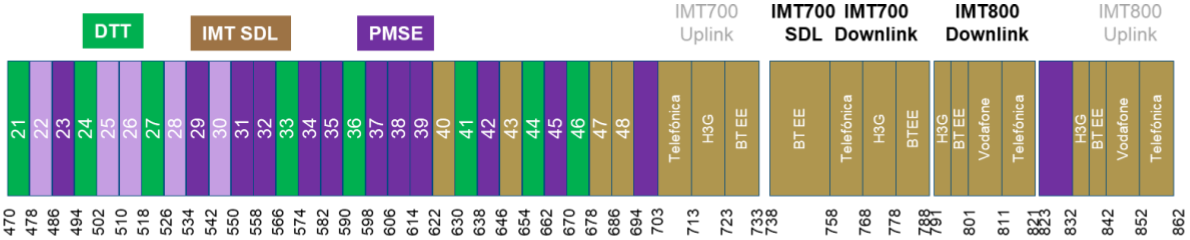
Additionally, by 2030 there will be higher proportion of TV devices capable of supporting H.265/HEVC video coding which is able to deliver video at the same quality as H.264/AVC MPEG4 with almost another 50% reduction in bitrates relative to H.264/AVC. H.265/HEVC coding would allow one or more of the DVB-T2 multiplexes to support more content.

A transition to DVB-T2 may also allow more freedoms to exploit larger Single Frequency Network (SFN) designs than was possible with DVB-T. SFNs may allow some small coverage improvements too at transmitter service area boundaries but SFNs can principally offer some modest gains in spectral efficiencies for multiplexes which do not require regional programming or advertising content. In the above illustration for case 2b, the DTT network could use a Multi Frequency Network (MFN) design carrying regional content with the second PSB multiplex but the other two multiplexes could exploit larger SFNs. The precise re-engineering of the DTT network, choices of coding and modulation rates, use of guard intervals for SFNs, etc. is open for further exploration and study, but the principal that DTT spectrum can be released as a dividend for IMT and PMSE through technology refreshes, without materially impacting DTT consumers in the event there is some decline or consolidation in TV programmes, and little additional HDTV demand is key for any IMT SDL spectrum to be released.

4.2.1 IMT under co-primary – case 2: invest in DTT for IMT SDL

Case 2a is where a modest investment can be made to the DTT network to create a measurable spectrum dividend for IMT SDL (and for PMSE) use. In Case 2a, it should be possible to release two multiplexes resulting in at least 16 MHz for IMT SDL. In areas where there is overlap from two main broadcast transmitters there can be up to four 8 MHz channels available for use for IMT SDL, or 32 MHz available. For example, one area of such DTT overlap is York which is served at similar levels by the Bilsdale and Emley Moor DTT Transmitter stations. The Exhibit below illustrates an example of an IMT SDL allocation in York. Six multiplexes on UHF channels 21,24,27,40,43 and 46 are transmitted from Bilsdale. Six multiplexes on UHF channels 33,36,41,44,47 and 48 are transmitted from Emley Moor. In this example, UHF channels 40 & 43 from Bilsdale and channels 47 & 48 from Emley Moor are vacated and reassigned for IMT SDL. There are no DTT relays in York, but relay frequencies would also need to be considered as a general rule too. In this example, each of the four UK MNOs could each use 8 MHz for example, or one MNO use 16 MHz and two other MNOs use 8 MHz each. The PMSE channels 22,25,26,28 and 30 are useable indoors only as these UHF channels are used at the Belmont DTT transmitter which does not serve York for DTT but would otherwise may have some interference exposure to some outdoor PMSE applications.

Exhibit 24: Co-primary use for 470-694 MHz scenario – example spectrum allocations – case 2b



Source: Coleago Consulting

Case 2b is where a larger investment can be made to the DTT network to create a larger spectrum dividend for IMT SDL (and PMSE) use. In Case 2b, it could be possible to release three multiplexes resulting in at least 24 MHz for IMT SDL. Again, in areas of DTT service area overlap, the IMT SDL spectrum could be 48 MHz.

Often DTT channels are grouped in non-contiguous channels as this can allow for practical transmitter combiner solutions to be implemented at DTT sites. This would mean that any IMT SDL spectrum dividend would in general be non-contiguous. If any single MNO acquired non-contiguous 8 MHz blocks, carrier aggregation would be required which may add some complexities including reliance on device carrier aggregation combinations support. There can also be a higher risk of Passive Intermodulation (PIM) interference into the IMT700 band and even the IMT800 band if combining fragmented IMT SDL spectrum blocks.

In addition to expecting fragmented spectrum blocks and the total of these fragmented blocks being a variable around the UK of between 16 to 32 MHz, these IMT SDL spectrum blocks may also be spread across the entire 470-694 MHz range. An MNO hosting their existing low-band IMT spectrum, and this proposed UHF IMT SDL spectrum on the same base station antennas will present additional challenges if SDL spectrum is wide banded. For example, if IMT SDL spectrum towards the lower end of the UHF spectrum is used this would almost certainly require a second set of antennas at sites, which could place practical constraints on the attractiveness or value of such spectrum. In the York example above, the IMT SDL spectrum was intentionally selected to be at the top end of the UHF band meaning there can be more practical base station antenna solutions to host existing MNO low-band and IMT SDL spectrum. For example, state-of-the-art base station antenna bandwidth at low band can currently support 617-862 MHz.

It would be possible for IMT to use more spectrum beyond that which is released by the DTT network consolidation. It would be possible for IMT SDL to use the white spaces or interleaved spectrum between the main DTT broadcast sites, much in the same way PMSE uses interleaved spectrum. This IMT SDL approach in using interleaved spectrum would however directly impact spectrum available for PMSE. It may be possible for PMSE and IMT SDL to both share interleaved spectrum but requires much more detailed coordination effort. The idea of MNOs not deploying IMT SDL in certain locations where PMSE might have high demand, in return for PMSE having access to less interleaved spectrum elsewhere is one idea for further exploration. A version of this geographic sharing idea is presented below at Section 4.2.8. This interleaved approach to IMT SDL should be considered more fully only if there is more certainty in the emergence of an SDL IMT eco-system.

4.2.1 PMSE under co-primary– case 2: invest in DTT for IMT SDL

In the event DTT supply declines and IMT SDL is adopted in a “co-primary use for 470-694 MHz” scenario, at best there would be no more or no less interleaved spectrum available for PMSE use, since DTT multiplexes have been replaced by IMT SDL allocations.

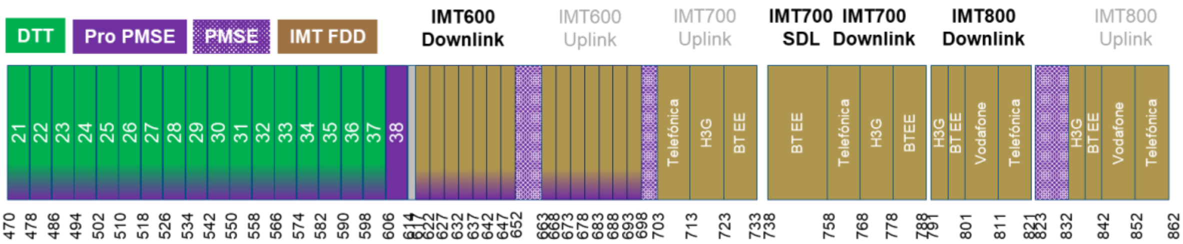
However, high demand PMSE use is largely predictable in terms of location and time. High demand is typically observed geographically at for example theatres and large conference venues, and in time at performance arts festivals, touring acts, and at sporting events. It may be possible that for say the largest events and locations across the UK where PMSE is expected to need peak spectrum quantities, that coordination of the IMT SDL spectrum can be managed through a third-party spectrum management function (such as Ofcom or other entity). In this case, the IMT SDL spectrum which is assigned to an MNO agrees not to activate this IMT SDL spectrum on its sites surrounding the location needing high-demand PMSE spectrum. Such a geographic sharing model between IMT and PMSE is examined in the next scenario and would apply generally for all cases where IMT consumes spectrum below 694 MHz.

4.3 IMT600 band plan - broadcast & mobile services split in 470-694 MHz

Our indicative set of key trends for this scenario is as follows. Mobile data demand continues to grow at a similar level to the previous five years and rural areas experience congestion. Linear TV declines steadily; a sizeable minority still watches linear TV. Broadcasters continue to question the viability of their channel mix in terms of meeting their financial and PSB objectives. However, there is external investment made into the DTT platform to engineer an IMT600 spectrum dividend whilst at the same time providing a meaningful additional payload capacity for DTT for providing a means for additional HDTV content delivery, through opportunities in network re-design. PMSE demand continues to grow moderately.

In this scenario, the current 470-694 MHz spectrum range is divided into two ranges. The first range is between 470-606 MHz and allocated to broadcast on a primary basis with mobile on a secondary basis. The second range is between 606-694 MHz and allocated to mobile IMT on a primary basis. The portion allocated to mobile IMT is designed to accommodate the 2x35 MHz 3GPP Band 71/n71, or the recently approved 2x40 MHz APT 600 MHz band plan which is awaiting assignment of a 3GPP Band number[54], or sub-sets of these band plans. The Exhibit below depicts a 2x35 MHz Band 71 arrangement for IMT600 as an example including the existing UK mobile operator allocations up to 862 MHz for reference.

Exhibit 25: Broadcast and mobile split in 470-694 MHz scenario – spectrum allocation for DTT, IMT & PMSE



Source: Coleago Consulting

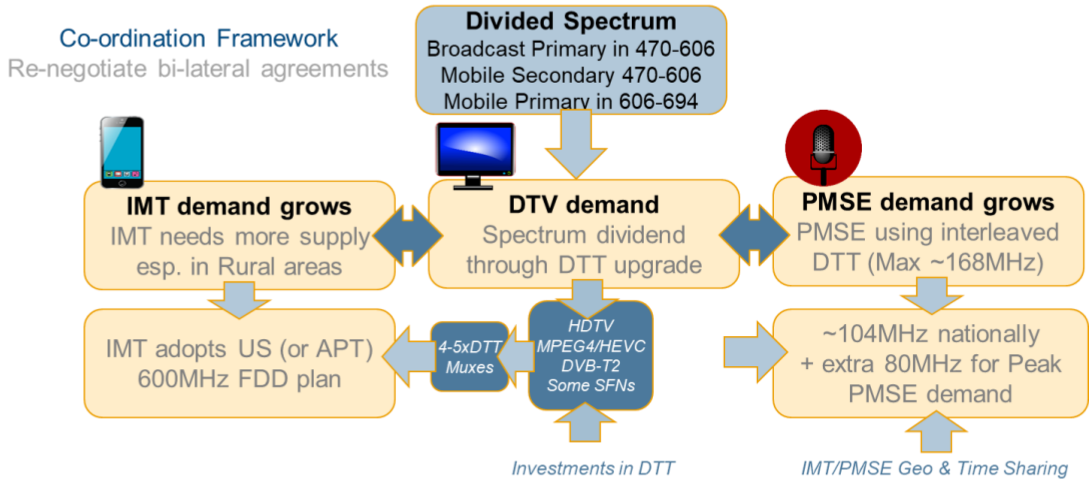
Unlike the "co-primary use for 470-694 MHz" scenario, this "broadcast and mobile split in 470-694 MHz" scenario is not dependent upon the emergence of an IMT device eco-system as 3GPP Band 71 is deployed and is used in the US and Canada, with several other countries looking to also deploy this band. The attractiveness or value of the IMT600 FDD band plan to UK MNOs will, to some extent, depend on the success of Band 71 deployments elsewhere in the world, as this drives more devices supporting Band 71. Currently, 600 MHz (Band 71) device support is lower than for 700, 800 or 900 MHz bands, but would be expected to close the gap in the coming years.

This "broadcast and mobile split in 470-694 MHz" scenario may become more relevant if there is no or a delayed IMT SDL standardisation, specifications, and emergence of an IMT SDL device eco-system. Any device eco-system takes several years to be adopted with critical mass to be of value to MNO's. Because of this, an IMT600 FDD band plan is expected to be more valuable to MNOs even if IMT SDL emerges in the coming years. Band 71 will have had several years head start on IMT SDL in UHF.

Unlike the "no change to 470-694 MHz" and "co-primary use for 470-694 MHz" scenarios, this "broadcast and mobile split in 470-694 MHz" scenario may be influenced by higher confidence in being able to mitigate or tolerate interference risks posed from high power DTT transmissions in neighbouring countries being co-channel with the uplink of the FDD based IMT600 networks in the UK. This co-channel interference mechanism is typically cited as the most challenging barrier for any co-primary use of the bands as coordination distances of over 200km are ideally needed. However, these co-channel interference risks are examined further in this scenario, along with mitigation considerations.

[54] https://www.gsma.com/spectrum/wp-content/uploads/2022/06/Low-band-Spectrum-for-5G-Infographic.pdf

Exhibit 26: Broadcast and mobile split in 470-694 MHz scenario - evolution case for DTT, IMT and PMSE



Source: Coleago Consulting

This “broadcast and mobile split in 470-694 MHz” scenario can only be possible if the spectrum for DTT could be reduced from 216 MHz to 136 MHz. In the previous scenario IMT SDL spectrum was shown to become available through any reduction in the number of DTT multiplexes brought about by a market/policy led reduction in programme content, or an investment led spectrum dividend by upgrading video coding, or a more aggressive investment led spectrum dividend by also upgrading to DVB-T2. For this “broadcast and mobile split in 470-694 MHz” scenario, a full 80 MHz of DTT spectrum needs to be re-farmed. This scenario could only realistically be achieved if there were significant investments in video coding, multiplex upgrades to DVB-T2, and DTT network re-design. As such, only one case is shown for this scenario, which is the case where the DTT network receives such investment.

4.3.1 DTT under IMT600 band plan

As illustrated for the “co-primary use for 470-694 MHz” scenario the higher-level investment case (case 2b) is built upon investment in both video coding and DVB-T2 to support approximately all remaining TV content in about half the spectrum, or three multiplexes in total. If the current DTT network with its six multiplexes are occupying 216 MHz of UHF spectrum, then this equates to an empirical spectrum re-use factor of approximately 216 MHz/ (6x8 MHz) = 4.5 across all multiplexes. We understand that the three PSB multiplexes have a spectral re-use of around 5:1 and the three commercial multiplexes have a spectral re-use of around 4:1. If three DVB-T2 multiplexes with H.264/MPEG4 coding can approximately support today’s TV payload in terms of programmes (without HDTV upgrades) by the early 2030s, then this in theory could free up around 108 MHz assuming the same spectral re-use factor. This is 28 MHz more than the 80 MHz required for the IMT600 FDD band plan to be created, and hence could be seen as overly aggressive. This reduction to three multiplexes would also limit any headroom for DTT platform growth for introducing HEVC coding or more HDTV content than today.

Assuming a similar spectral re-use factor of 4.5 is used, then if there were four DVB-T2 multiplexes (say two PSB and two commercial) then this might require 4.5*(4*8 MHz) = 144 MHz of DTT spectrum. An IMT600 FDD assignment requires 80 MHz clearance meaning that 216-80 MHz = 136 MHz would be available to DTT. There is only an 8 MHz difference in these spectrum quantities, and it may be entirely possible to support four DVB-T2 multiplexes through network re-design and exploiting a little more aggressive frequency re-use than currently observed. The current DTT network is designed largely based on Multi Frequency Network (MFN) designs and appears to have exploited some Single Frequency Network (SFN) designs to accommodate the 700 MHz spectrum clearance[55]. DVB-T2 will allow more SFN design freedoms over DVB-T and as such more aggressive spectral re-use could be afforded by a more extensive use of regional size SFN designs in a DVB-T2 based DTT network. Various studies have shown modest spectral efficiency gains of the order 10%-20% can be achieved through the adoption of wider area SFN designs considering statistical multiplexing efficiencies too[56]. It is recognised that a national SFN is impractical for a country the size of the UK, but larger area SFN designs are an opportunity to exploit a lower spectral re-use factor where regionalised TV

[55] https://www.ofcom.org.uk/spectrum/information/transmitter-frequency
[56] https://tech.ebu.ch/docs/techreports/tr029.pdf

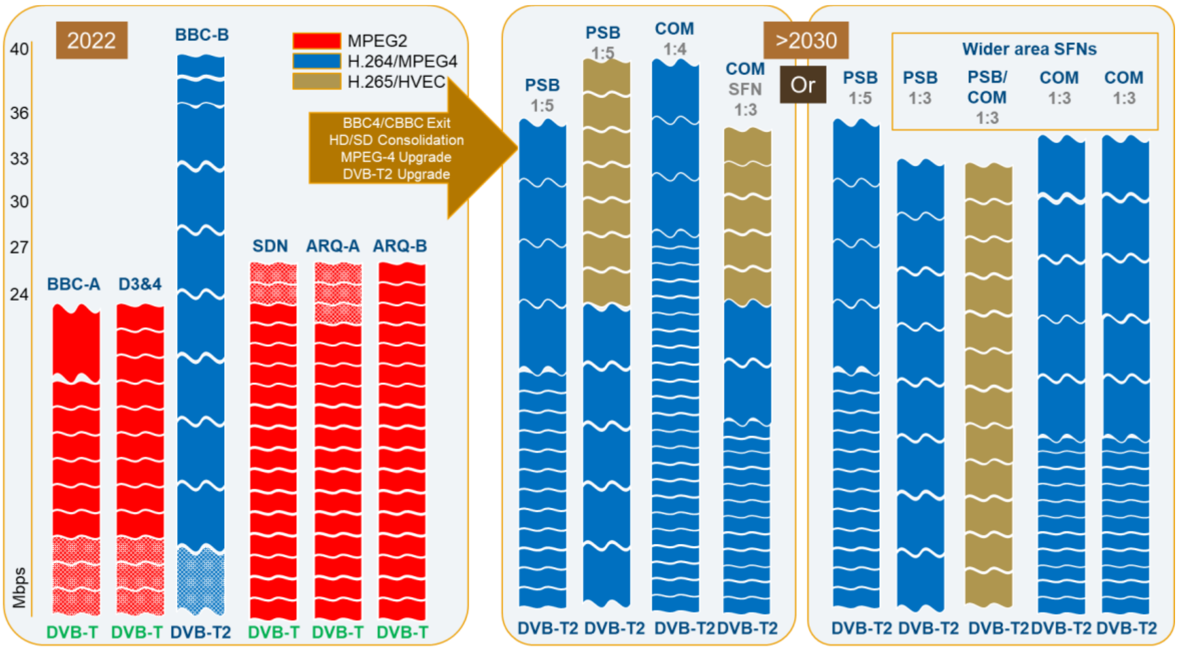
content (news and advertising for example) is not needed or not needed to precisely align with programming boundaries. It may also be possible to re-arrange TV programme content so that TV programmes without regional content can be hosted on multiplexes designed with more aggressive SFN guard intervals to form wider area SFNs and which do not need to adhere to BBC and ITV TV regional boundaries. This may also suggest a different multiplex licencing model is needed, one which is more aligned to capacity slots on multiplexes rather than whole multiplexes. In this case BBC, ITV, and Channel 4 regional TV content could for example share the same MFN multiplex design as they both have regionalised content in terms of news and advertising. On the other hand, TV programmes without regionalised content (e.g., Channel 5, BBC Three, Film4 and others) could share the same SFN multiplex design.

A four DVB-T2 multiplex DTT network using one multiplex as part of a wider area SFN design could deliver an estimated 152Mbps. This could include one PSB DVB-T2 multiplex (offering around 98.5% coverage) at 36Mbps, one PSB DVB-T2 multiplex offering around 95% coverage at 40Mbps (similar to the current BBC-B multiplex), one commercial multiplex offering around 95% coverage at 40Mbps and another commercial multiplex running at around 33Mbps using an SFN with an assumption that 1:3 effective spectrum re-use can be achieved. This 152Mbps capacity does represent a 10% decrease in absolute capacity relative to today's six multiplexes delivering 169Mbps, but the video coding upgrades will allow significantly more channels (programme payload) to be supported including the ability to offer HDTV services, and could support the required HDTV growth planned, subject to further evaluation and review of how DTT evolves in its current form

Alternatively, the use of five multiplexes where four multiplexes are used as wider area SFNs to permit a lower frequency re-use of 1:3 could deliver an estimated 174Mbps, which slightly exceeds today's DTT network capacity of 169Mbps. This implementation would additionally offer the DTT platform well over 50% additional payload capacity if H.264/MPEG4 is used in all multiplexes relative to today's DTT platform, afforded by H.264/MPEG4.

This concept is illustrated conceptually in the Exhibit below, where we have additionally shown some HEVC coded channels for further HDTV content and growth opportunity. The exact design choices and trade-offs are all subject to further analysis and highly dependent upon the timing and business models in offering more HDTV, TV receiver penetration rates, and subscriber consumption of HDTV in the coming years and is an area recommended for further research by this study. The general concept that a dividend and additional DTT HDTV capacity is possible is the key message.

Exhibit 27: Broadcast and mobile split in 470-694 MHz scenario – example of DTT multiplex arrangements



Source: Coleago Consulting

Additionally, by 2030 there will be higher proportion of TV receivers capable of supporting H.265/HEVC video codec which is able to deliver video at the same quality as MPEG4 with almost another 50% reduction in bitrates. H.265/HEVC coding would allow even more HDTV content for example. All TV receivers since around 2018 have been sold with HVEC codec support. More recently the latest codec technology, H.266 or Versatile Video Coding (VVC) has been recently added to the DVB specifications[57]. By the mid-2030s, it might be reasonable to assume that virtually all DTT households would then be able to support the HVEC video coding, then a few years later most DTT households able to support VVC coding. Furthermore, this ensures a path for DTT to continue to deliver its vital service across the UK, with some positive growth opportunity but certainly without any compromise relative to today's DTT payload.

Although not shown as a case under this scenario, it is also entirely possible for all TV channels to be converted to HEVC coding by the early 2030s albeit at additional costs, as this may require a funded program of TV set replacement or issuance of set-top boxes to support HEVC. Such HEVC deployment models have been introduced in other countries (such as Germany and the Netherlands) over the last few years. In such a scenario, using five DVB-T2 multiplexes and HEVC coding, a digital dividend for IMT600 is supported whilst at the same time providing a significant upgrade for HDTV payload capacity.

4.3.2 IMT under IMT600 band plan

Assuming DTT spectrum can be reduced from 216 MHz to 136 MHz in the UK, there also needs to be reasonable confidence that an IMT600 FDD band plan can in principle co-exist with the DTT network and more importantly with DTT networks in Ireland, France, the Netherlands and Belgium.

Regarding co-existence of IMT600 with the DTT network, the DTT network would be assigned below 606 MHz, and the IMT600 networks could follow a 3GPP Band 71 arrangement. This would create an 11 MHz guard band between DTT and IMT600 downlink, where the guard band includes the entire PMSE Channel 38 band. This spectrum arrangement is not dissimilar to when the IMT800 downlink was adjacent to DTT spectrum during the original spectrum dividend at 800 MHz during the early 2010s. However, with IMT800 there was only a 1 MHz guard band between DTT and IMT800 downlink, and many households and especially dwellings with community TV amplifier systems which were close to IMT800 base stations, and receiving DTT delivered on Channel 60, were issued with an RF filter for connection to the domestic TV aerial as an interference mitigation measure. In the case of a proposed IMT600 band plan with an effective guard band of 11 MHz, this adjacent system interference issue would be seen as less problematic. An APT600 FDD band plan would reduce the guard band down to 6 MHz. However, it would be prudent to assess these aspects in more detail as part of a future study of simulations and canvass the experience of real-life interference incidents when IMT800 and DTT were adjacent.

The more pressing issue of DTT and IMT600 FDD co-existence is the risk of interference from DTT Transmitters outside of the UK which would be co-channel to the IMT600 FDD Uplink channels. This is typically claimed as the overarching reason preventing a co-primary allocation where mobile services are using an FDD or TDD band plan. The worst-case conditions arise when a HPHT DTT broadcast transmitter in a neighbouring country is co-channel with an IMT600 base station in the UK having an elevated directive antenna pointing toward the HPHT DTT transmitter. There have been several studies[58] which have examined this interference mechanism using different modelling and simulation approaches. Depending on the I/N protection criteria, % time of interference, land/sea paths, and of course the basic DTT and base station parameters, coordination distances of between 150km and 400km have been cited. These coordination distances also assume there are no mitigation measures implemented.

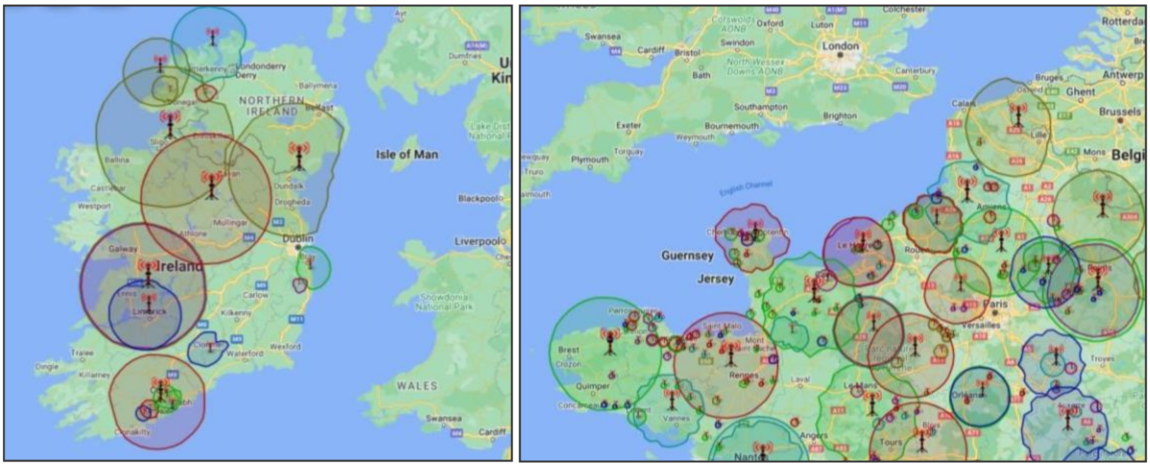
Inspection of public domain sources of European DTT networks reveal that the Republic of Ireland only operates two multiplexes using DVB-T for its DTT network. Assuming that the Republic of Ireland is not planning to increase the number of its multiplexes, the Republic of Ireland is in a potentially stronger position than the UK to repack its multiplexes and take advantage of a spectrum dividend for IMT600 FDD and given its more rural demographics may even have a stronger need for IMT600 than the UK. Analysis of the main broadcast transmitters in the Republic of Ireland indicates that all the higher power UHF channels which would be co-channelled with IMT600 FDD uplink (UHF Channels 45 to 48) are generally transmitted from DTT sites in the West of the Republic of Ireland, with the exception of the Clermont Cairn DTT site which uses Channel 45 in the very northeast of the Republic of Ireland which serves both the Republic of Ireland and Northern Ireland. These Republic of Ireland DTT sites would impact Northern Ireland's ability to adopt IMT600, assuming that the Republic of Ireland doesn't wish to pursue an IMT600 route. It does appear that Clermont Cairn also employs significant azimuthal filtering of up to 20dB directed at England, which will mean less impact into northern England and Wales. Regardless of how the Republic of Ireland chooses the future of its UHF spectrum, the fact there are only two multiplexes, and potentially only one channel on one DTT transmitter (Clermont Cairn) which would ideally need a different channel provides scope for a relatively straightforward amendment of bilateral agreements between the UK and Ireland. Of course, if the UK wants to pursue an IMT600 dividend but the

[57] https://dvb.org/news/dvb-adds-vvc-to-its-video-coding-toolbox/

[58] https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-BT.2337-1-2018-PDF-E.pdf

Republic of Ireland does not want to adopt IMT600, then any re-engineering and impacts upon Ireland would need to be negotiated and ultimately funded by the UK. If all these options might fail, then the UK MNO's can adopt a number of mitigation measures which are described below.

Exhibit 28: Broadcast and mobile split in 470-694 MHz scenario – DTT sites in Republic of Ireland and France occupying channels 45 to 48 being co-channel with IMT600 FDD uplink sub-band



Source: fmscan.org and Coleago Consulting

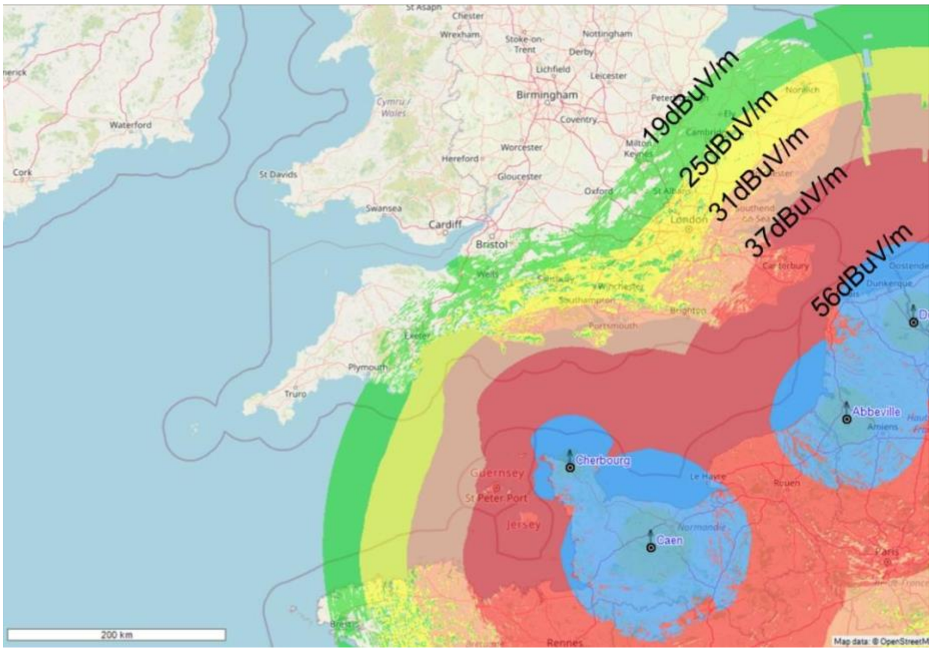
Inspection of the Netherlands DTT networks reveals that most DTT sites are Medium Power, Medium Tower (MPMT) with no DTT transmitter exceeding 20kW ERP power, with most coastal DTT sites also employing azimuthal radiation patterns with attenuation towards the UK. Initial estimates of DTT field strengths in the UK indicate that UK IMT600 FDD networks should not be impacted by Dutch DTT transmissions.

The Belgium DTT networks currently use only two national multiplexes and one local multiplex. The entire Belgian DTT networks occupies only six UHF channels through extensive use of SFNs. The six DTT channels are however above UHF channel 40 which would impact coordination with IMT600 FDD networks in the UK. The Belgian broadcaster RTBF has indicated that it plans to switch off its DTT network by 2027[59], which would take Belgium to two multiplexes consuming only four UHF channels. Given that Belgium is expected to eventually need only four UHF channels but may have been allocated several more UHF channel slots from the original Geneva 2006 coordination efforts, this suggests that there could be some scope at least for further exploration in the adjustment of bilateral agreements. Belgium may also be interested in exploring an IMT600 FDD band plan, which would mean that UK and Belgium would be further incentivized to reach agreement.

Analysis of the French DTT network reveals a more extensive use of High-Power High-Tower DTT broadcast sites. The French DTT network has similarities to the UK DTT network in that there are six national multiplexes although all are using DVB-T, but all TV channels use MPEG4 encoding indicating that all of the 216 MHz is being consumed. The worst-case interference scenario from France appears to be from UHF Channel 45. Using the same methodology and propagation modelling as used for the coordination studies in ITU-R Report 2337-1, the following plot depicts the estimated field strength from French DTT broadcast sites with Channel 45 using published ERP values of French DTT transmitters together with nominal omni-directional patterns for simplicity. The 19dBμV/m contour represents the case where there would be a -6dB I/N threshold exceeded for 1% of the time at an IMT600 base station uplink receiver using a directive panel antenna at 30m height and directed towards France. The 25dBμV/m contour represents a relaxation of the I/N to 0dB. The 31dBμV/m contour represents a -6dB I/N threshold when using a base station antenna with a polarisation orthogonal (V-Polarised) to the French DTT sites (DTT from France is horizontally polarised), and the 37dBμV/m contour represents a 0dB I/N with orthogonal polarised antenna at the base station.

59 https://www.broadbandtvnews.com/2022/01/05/rtbf-wants-to-switch-off-fm-and-dvb-t /

Exhibit 29: Estimated field strength values exceeded for 1% of the time from French DTT sites using channel 45



Source: Coleago Consulting

The plot above was calibrated against previous studies from the ITU as a benchmark, which had assumed a 30m base station antenna height and a nominal 3° antenna down-tilt. Most base stations in the UK are however closer to 15m in height which should afford around 6dB additional protection. If the mitigation techniques of using vertically polarised antennas and accepting a 0dB I/N threshold are used with 15m base stations, then most of the UK IMT600 base station sites in South-East England could be reasonably protected.

A potentially very powerful interference mitigation option which could be used is to have IMT600 FDD as a component carrier in a carrier aggregation combination and intentionally disable the IMT600 uplink component. If 3GPP Band n71 is deployed in the UK, it will likely be a component carrier of a carrier aggregation combination since it is a band which is being added much later than other 5G bands. In such a scheme the downlink may have for example carrier aggregation across say 700 and 600 MHz bands, with 700 MHz as the primary layer and only use 700 MHz for the uplink. In this way, the IMT600 FDD is effectively configured to perform as an SDL component. Such a technique could be used as a more general coordination enablement tool, to allow different countries across Europe to adopt IMT600 at different times for example. This is an area recommended for further investigation.

Additionally, base station antenna tilting typically can provide up to another 10dB rejection toward the horizon, albeit at the expense of some coverage loss, or pointing a base station sector away from DTT could allow another 10dB rejection, also at the expense of coverage loss. There are other interference mitigation techniques available from RAN vendors which include Interference Rejection Combining (IRC) algorithms at baseband. There are also 3rd party solutions which specialise in removal of specific interference through adaptive processing of baseband signals accessed via the digital Common Public Radio Interface (CPRI). Such adaptive solutions have been used in several real-world deployments and have shown to provide over 20dB rejection of TV broadcast interference in the IMT700 MHz bands, although these solutions often exploit polarisation diversity as part of their rejection capability. These additional mitigation measures could be used at IMT600 sites which may be more exposed to DTT interference such sites along elevated portions of the south and south-eastern coastlines.

France will make its own decisions regarding the future of its UHF spectrum from 2030. France also needs to consider more border areas than the UK does. Of note, France has the highest adoption of IPTV Households in Europe which surpasses DTT adoption by over four times. France might be encouraged to pursue an all-IPTV future for its TV meaning there could be appetite for France to explore an IMT600 route similar to this scenario being examined. If so, then coordination with the UK would be in the same interests, although coordination with Italy, and other countries may be less so.

IMT600 downlink will be adjacent to Channel 38 PMSE unlicenced band. This poses some Out of Band (OOB) interference risk from IMT600 downlink to PMSE when in close proximity. As Channel 38 PMSE is an unlicenced band there is no way of knowing where the PMSE users may be, so geographic coordination is not possible. If 3GPP Band n71 is adopted for IMT600 then there would be a 3 MHz guard band between the bottom of IMT600 at 617 MHz and the top of the PMSE unlicenced band at 614 MHz. This size of guard band is similar to guard bands adopted elsewhere to provide some protection to PMSE, for example the 2 MHz guard band between 821 MHz (top of 3GPP Band 20 downlink) and 823 MHz (bottom of unlicenced PMSE in the 800 MHz duplex gap). However, it is strongly recommended that this be studied further to assess interference risks. In the event there is some interference risk, OOB filters can be applied to IMT600 base stations to limit adjacent channel interference to PMSE Channel 38 devices. Similar OOB filters are in fact used at DTT main broadcast sites using DTT channels 37 and 39 which are directly adjacent to Channel 38, having no guard band. We presume such OOB filtering is also adopted at DTT relay sites also to protect unlicenced Channel 38 PMSE devices. As a benchmark, in the US, IMT600 base station downlink is also adjacent to the Radio Astronomy band (US Channel 37) having the same 3 MHz guard band, where OOB emissions are observed too.

4.3.3 PMSE under IMT600 band plan

In this scenario, 80 MHz is cleared for IMT use. If there are 17 x 8 MHz Channels or 136 MHz of DTT interleaved spectrum available using say 4x DVB-T2 multiplexes (as per our DTT example where one channel is dedicated to a large area SFN with re-use 1:3), then there would be 4 x 8 MHz = 32 MHz of unusable PMSE spectrum hence 13 x 8 MHz = 104 MHz of usable interleaved spectrum for PMSE. This assumes that 4x channels are occupied by DTT serving any area from a main broadcast transmitter. We believe this should adequately satisfy the general day to day requirements for the vast majority of professional PMSE uses.

An IMT600 band plan following Band 71 arrangement would also provide an 11 MHz duplex gap (652-663 MHz). Assuming a 2 MHz guard band adjacent to IMT600 downlink channels is needed, this duplex gap may provide another 9 MHz of PMSE spectrum albeit for non-professional applications, although 4MHz in the range 694-698MHz would now be occupied by IMT600. Overall, a net 5MHz of unlicensed PMSE is gained.

However, high demand professional PMSE use can require all of the interleaved DTT spectrum (current maximum being 168MHz where there is no DTT overlap) plus have to rely on other spectrum (e.g., unlicenced PMSE bands, aeronautical bands for PMSE, etc.) for very large events. Licenced PMSE spectrum is however largely predictable in terms of location and time. This predicable nature of high demand PMSE offers a potential mechanism by which the needs of high demand professional PMSE can continue to be met by enabling IMT600 and PMSE to share the spectrum through coordination. In such coordination, IMT600 deployed at MNO base station sites can be relinquished for temporary PMSE use through a spectrum management entity. If there are any locations which persistently demand above 104 MHz of interleaved DTT spectrum for professional PMSE, then these can be identified and IMT600 not deployed in such areas. With such a mechanism, high demand PMSE events could have access to the entire 614-694 MHz spectrum range = 80 MHz on top of the approximate 104 MHz of DTT interleaved spectrum or 184 MHz total professional PMSE spectrum. The PMSE spectrum available from the DTT interleaved spectrum (using the same assumptions) from the current UK DTT network and its six multiplexes in 216 MHz of DTT spectrum would be 216 MHz-(6*8) MHz = 168 MHz. Therefore, such IMT/PMSE geographic sharing offers the PMSE industry an opportunity to effectively increase its spectrum for professional PMSE by 16 MHz and non-professional PMSE applications by around a net 5MHz (via the Duplex Gap), where PMSE needs such spectrum.

Exhibit 30: Estimated spectrum available for professional PMSE applications for an IMT600 band plan with a nominal PMSE/IMT geographic sharing model

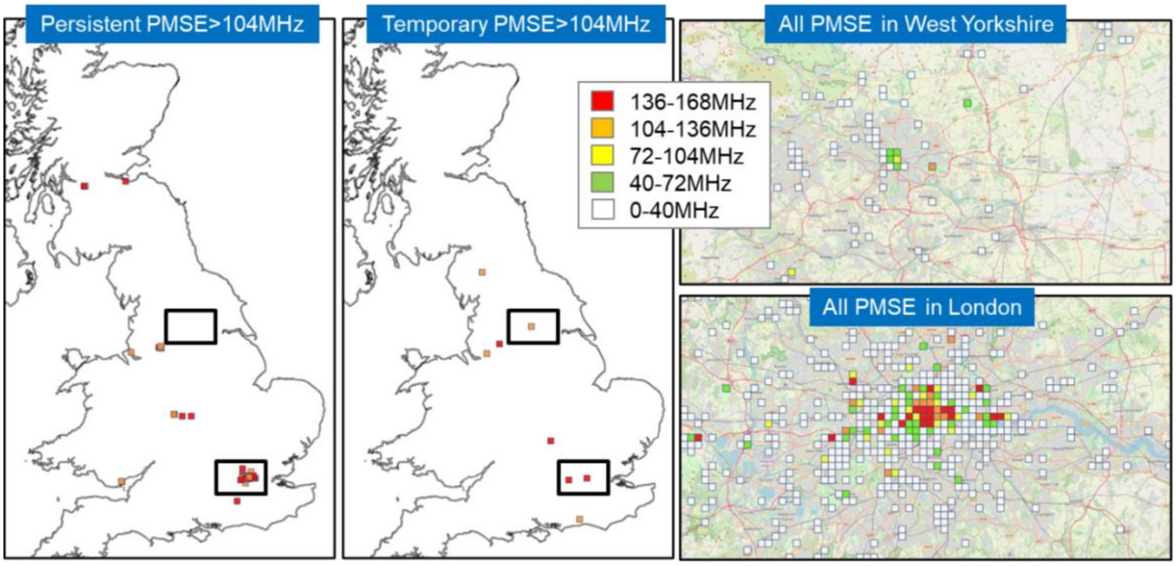
	No change	IMT600
DTT Spectrum	216	136
IMT Spectrum	0	80
DTT Spectrum in use at locale	48	32
Interleaved PMSE Spectrum	~168 (Max)	~104 MHz ~184 MHz (Max)

Source: Coleago Consulting

As discussed earlier, a request was made to Ofcom for PMSE licence data over a 12-month period, issued in the 470-703 MHz range. The data provided included bandwidth, centre frequency, location (as 1km^2 bins), and the duration of licences. This data was processed to gain a better understanding of the spatial and temporal demand of PMSE Spectrum. The Exhibit below depicts the peak PMSE bandwidth over a 12-month period as a function of location, for all locations with PMSE bandwidths >104 MHz. This means all touring performance arts, festivals, conferences and other temporary users of licenced PMSE are also captured in this data. The PMSE bandwidth in any location here is maximum of the daily summation of all actual unique spectrum licenses, where any narrowband license such as 0.2 MHz licenses are considered to effectively occupy approximately 0.5 MHz in real bandwidth terms thus recognising the needs of multi-channel PMSE inter-modulation management. We observed about a 1:2.5 licensed bandwidth to occupancy bandwidth ratio in the data for the locations which used many 0.2 MHz licences, and clearly adopting a frequency plan to manage intermodulation interference. Furthermore, the Ofcom data implicitly captures all areas in the UK and hence includes those areas where there is DTT overlap and potentially less than 168 MHz of available interleaved spectrum available for PMSE.

Our analysis of the Ofcom data indicated that there were around 40 unique 1 km^2 locations across the UK which had persistent PMSE bandwidths in the interleaved DTT spectrum >104 MHz over the 12-month period. Persistent users were those with licences for over 30-days at any time over the 12-month period. Additionally, there were eight locations across the UK which had temporary (having licences for less than 30 days) PMSE bandwidths >104 MHz. This would suggest that so long as MNOs agree not to activate IMT600 in such locations with an agreed exclusion zone, there could be a manageable and harmonious outcome in that IMT600 can be deployed across all but a few locations in the UK, and in those few locations PMSE can enjoy using at least 16 MHz additional professional PMSE spectrum, and 5 MHz additional unlicensed spectrum including a contiguous 80 MHz of spectrum where PMSE needs peak spectrum. In the Exhibit, London and the conurbation of West Yorkshire are shown in detail. The area around the West End theatre district in London is clearly visible. However, our analysis indicated that there was only one location in West Yorkshire needing greater than 104 MHz PMSE bandwidth for two days in a 12-month period. This analysis implies that IMT600 could be deployed across West Yorkshire with one location needing some simple coordination over the course of a year. Additionally, our analysis also shows that for West central London PMSE could enjoy an extra 16 MHz of PMSE spectrum where IMT600 would not be deployed.

Exhibit 31: Licenced PMSE Spectrum over the period Oct 2021- Sept 2022



Source: Ofcom and Coleago Consulting

Additional analysis of the Ofcom data also reveals that there is a very large proportion of PMSE devices licensed in the 600 MHz range in the London area. If the above IMT/PMSE geographic sharing model is adopted, then PMSE re-tuning costs brought about by an IMT600 implementation would be minimised, as most of these 600 MHz PMSE licenses and devices could continue to be used. Although subject to further study, we believe that this should be significantly less than the PMSE re-tuning costs associated with the IMT700 clearance for example.

Apart from a geographic coordination model for IMT/PMSE sharing of the UHF band, there will also be a need to consider temporal sharing of the band for IMT/PMSE. In this case, the eight event locations identified in the above analysis such as festivals, performing arts touring events, and sporting events can be coordinated through a spectrum manager function where MNO sites using the IMT600 spectrum can agree to disable the spectrum during the period of the PMSE licences. Ofcom in part captures some of these events and have spectrum managers assigned for such major events. There were 26 major events identified by Ofcom for spectrum coordination for 2022[60], where such events lasted between one day and one week. In this case, PMSE users could on average observe an increase in available spectrum for PMSE when PMSE is needed most, at the acceptance that there may be less PMSE spectrum available in areas of more modest demand.

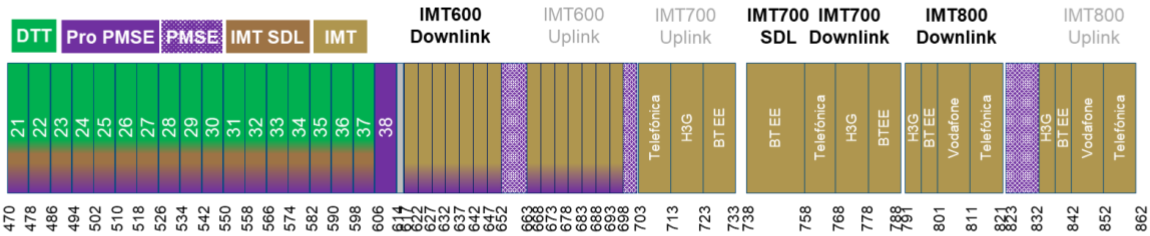
4.4 Transition to IPTV

Our indicative set of key trends for this scenario is as follows. Mobile data demand booms driven by a strong economic rebound to a shorter than expected recession. Users in rural areas experience significant congestion. Linear TV falls to low levels during the 2030s given the strong growth of SVoD and significant investment by the traditional broadcasters into their own online platforms. However, there is (government) investment made into the DTT platform to engineer the IMT600 spectrum dividend whilst at the same time provide a meaningful additional payload capacity for DTT for providing means for any additional HDTV content delivery, through opportunities for DTT network re-design. PMSE demand continues to grow moderately.

The second and third scenarios are brought together for this fourth scenario, where the 470-694 MHz spectrum range is divided into two ranges. The first range is between 470-606 MHz and allocated to broadcast and mobile on a co-primary basis. The second range is between 606-694 MHz and allocated to mobile on a primary basis. The portion allocated to mobile is designed to accommodate the 2 x 35 MHz 3GPP Band 71/n71, or the recently approved 2 x 40 MHz APT 600 MHz band plan which is awaiting assignment of a 3GPP Band number[49], or sub-sets of these band plans.

The first range between 470-606 MHz as a co-primary allocation would assume that any IMT services are deployed in the band are supplement downlink (SDL) and not FDD or TDD. The Exhibit below depicts the spectrum allocations in this range including the existing UK mobile operator allocations up to 862 MHz for reference.

Exhibit 32: Co-primary and mobile split spectrum for transition to IPTV scenario - DTT, IMT & PMSE

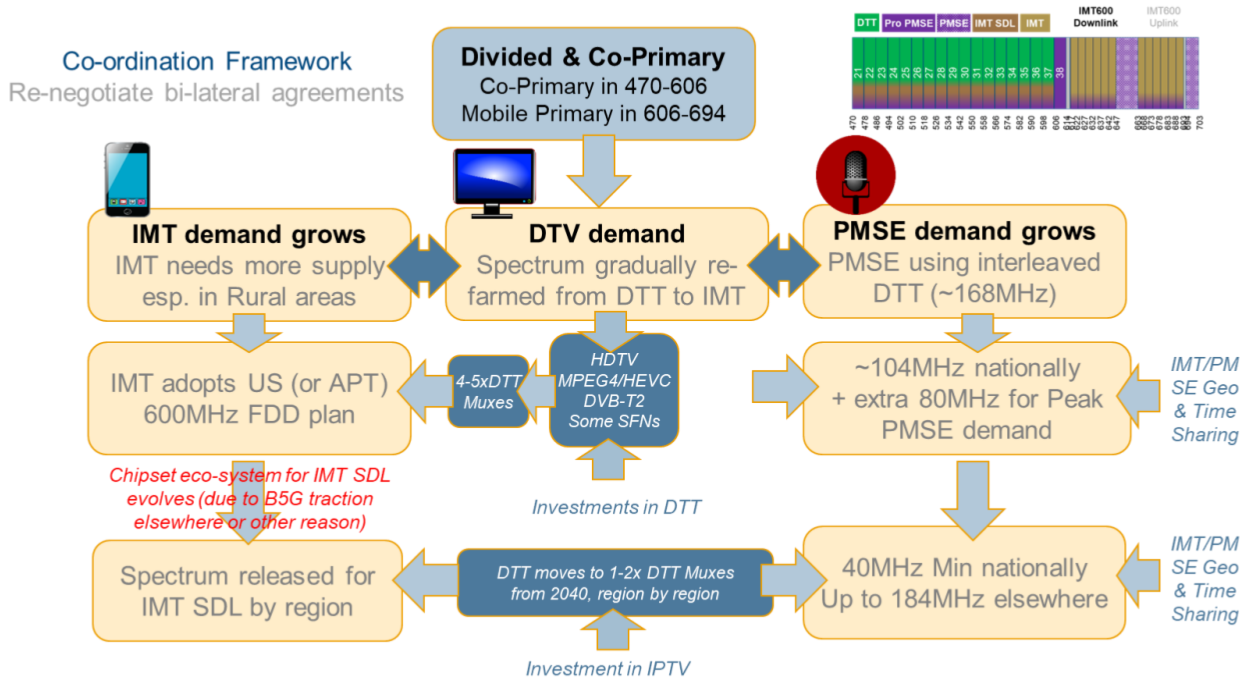


Source: Coleago Consulting

This fourth scenario allows IMT600 FDD networks to be introduced from the early 2030s as IMT600 FDD offers certainty given that Band 71 has a growing eco-system of devices, but also allows an IMT SDL component to be introduced in later years where its eco-system has yet to emerge. The band arrangement also permits a more gradual consumption of UHF spectrum by IMT and PMSE through re-farming most of DTT out of the UHF band in a longer-term horizon.

[60] https://www.ofcom.org.uk/manage-your-licence/radiocommunication-licences/pmse/events

Exhibit 33: Transition to IPTV scenario - evolution case for DTT, IMT and PMSE



Source: Coleago Consulting

In the longer term, PMSE and IMT become the symbiotic partners for sharing spectrum using geographic and temporal coordination, rather than today's DTT/PMSE symbiosis. In the longer-term PMSE may have a dedicated range of high-quality PMSE spectrum and through considered coordination with IMT, also have guaranteed access to differing amounts of the rest of the spectrum to cater for its unique variable spectrum requirements, at certain locations and/or times.

This scenario also requires investment into IPTV to ensure that IPTV can reach similar levels of population to at least the non-PSB DTT multiplexes do. The scenario also proposes that all PSB content would be hosted on one or two national DVB-T2 multiplexes leveraging HVEC video coding in the longer term. This means DTT can remain indefinitely to continue to deliver at least all the PSB content, and many additional popular TV channels, including HDTV content. A single DVB-T2 Multiplex with MPEG4 coding could deliver around 60% of today's total DTT content in HD or around 70% in SD, thereby serving an important parallel delivery of TV services to the UK

As per the third scenario "broadcast and mobile split in 470-694 MHz, this "transition to IPTV" scenario may be influenced by a higher confidence in being able to mitigate or tolerate interference risks posed from high power DTT Transmissions in neighbouring countries being co-channel with the Uplink of the FDD based IMT600 networks in the UK, as discussed in detail for the third scenario.

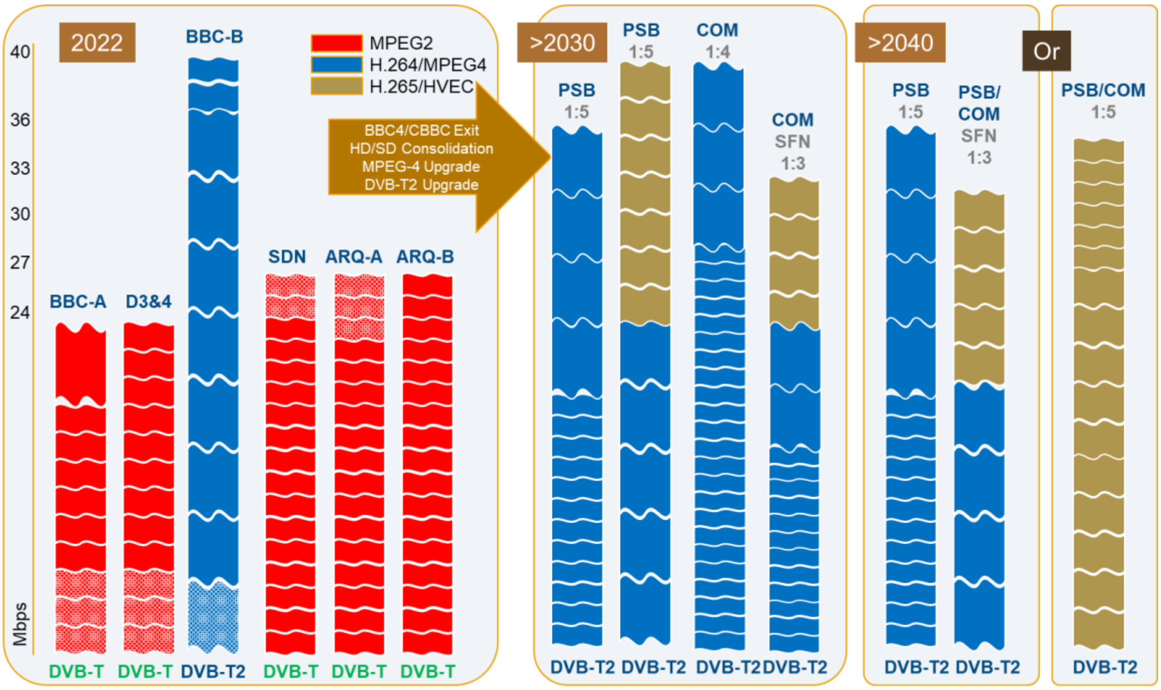
4.4.1 DTT under transition of DTT to IPTV

As detailed for the third scenario, the investment into the DTT platform is in upgrading both video coding and DVB-T2 in order to support approximately all TV content in 80 MHz less DTT spectrum. This may be just about be achieved using three DVB-T2 multiplexes but having four or five DVB-T2 multiplexes together with some additional design freedoms for larger area SFN on at least one Multiplex not carrying regionalised content will permit a release 80 MHz as a spectrum dividend for use in an IMT600 FDD band plan, and also provide some reasonable headroom for DTT platform growth in terms of supporting more HDTV content. The precise configuration of video coding, multiplexing of TV channels, and channel coding/modulation of DVB-T2 multiplexes would be subject to further study and network design choices, but as per the Scenario 3 analysis our initial analysis suggests that there should be modest opportunity for HDTV growth and IMT600 deployment in the 2030s.

Such investment into the DTT network would occur prior to 2030, such that an IMT600 band plan could be made available from the early 2030s. This ensures that there is no reduction in DTT supply for the 2030s. The transition to

IPTV would occur over a longer period, and perhaps by 2040s there would be sufficient households converted from DTT to IPTV to permit a further reduction in DTT multiplexes down to two or ideally one DVB-T2 multiplex. The concept of DTT platform multiplex migration is illustrated below.

Exhibit 34: Transition to IPTV scenario - example of DTT multiplex arrangements

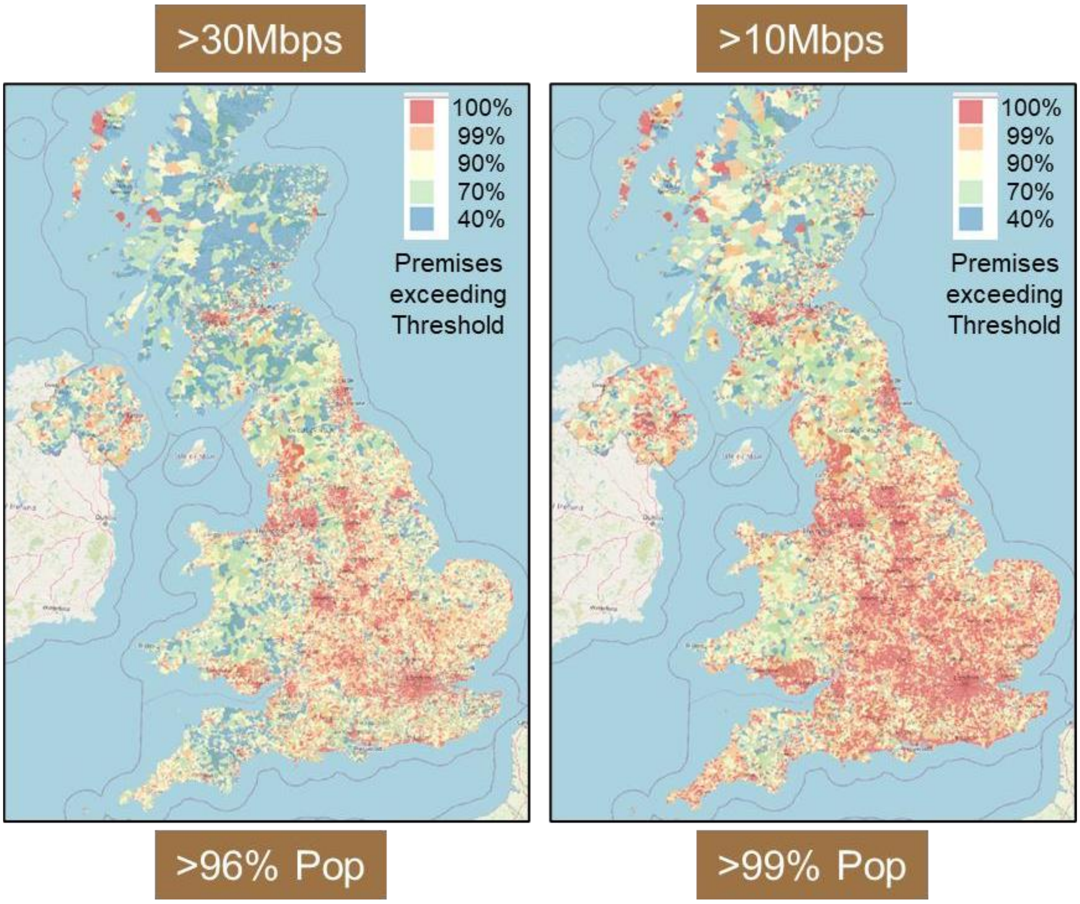


Source: Coleago Consulting

Transitioning to IPTV may also take place on a region-by-region basis. For example, London and SE England may be in a better position to transition to IPTV well before 2040 and before regions with more rural geography, or less broadband connectivity such as Scotland. The timing of IPTV transitioning is subject to further study. The precise investment in IPTV can be varied and again subject to further investigation and study but would include how digital skills gaps can be overcome so consumers can transition readily from DTT to IPTV, and provision of IPTV hardware and connection to broadband services so that IPTV can be delivered to any unconnected households.

The Exhibits below summarise the broadband availability across the UK as a function of the % of premises able to connect to a >30Mbps or to a >10Mbps broadband connection. This data was taken from the recently published Connected Nations update[50].

Exhibit 35: Broadband availability across the UK



Source: Ofcom and Coleago

Exhibit 36: Transition to IPTV scenario – broadband availability by % premises, by >10Mbps and >30Mbps as of May 2022

Access to Superfast services (>30Mbps)	Sept 2021	Jan 2022	May 2022
UK	96%	96%	96%
England	96%	97%	97%
Northern Ireland	91%	92%	93%
Scotland	94%	94%	94%
Wales	94%	95%	95%

Source: Ofcom

Exhibit 37: Transition to IPTV scenario – broadband availability by % premises, by >10Mbps and >30Mbps as of May 2022

Access to services (>10Mbps)	Sept 2021	Jan 2022	May 2022
UK	98%	99%	99%
England	99%	99%	99%
Northern Ireland	95%	96%	96%
Scotland	97%	97%	97%
Wales	97%	98%	98%

Source: Ofcom

Of note, BT now offer their new and existing BT TV Pro customers their TV service as an IPTV only or aerial free option. BT recommend that at least 22Mbps is needed for IPTV only services. It is expected that this is dimensioned on receiving HDTV service. For a SDTV service then a 10Mbps connection would be likely be considered as being acceptable.

Once IPTV services are deployed to a certain critical mass of households, then and only then should DTT be reduced from say 4x DVB-T2 multiplexes to two or potentially one DVB-T2 multiplex hosting all or most of the PSB content. What the critical mass should be is a topic for further study and could be something in the order of at least 98.5% of DTT households transferred to IPTV. In maintaining a single DVB-T2 multiplex allows a significant portion (i.e., 60% of viewed TV content) to still be delivered in parallel with IPTV, satellite and cable, and will reach households unable or unwilling or unreachable for IPTV and hence the last 1.5% of households. The timing of such a transition from 4x multiplexes to one will depend upon the investment made into IPTV roll-out, Household take-up, and any further decline in DTT programmes brough about by policy changes or commercial factors.

4.4.2 IMT under a transition of DTT to IPTV

There are both IMT FDD and IMT SDL allocations proposed for this scenario, which would be used by MNOs at different times from the early 2030s. The IMT FDD allocation follows that examined in the previous scenario where the DTT spectrum is reduced from 216 MHz to 136 MHz in the UK through investing in upgrades to video coding and DVB-T2 on the DTT platform thus permitting an IMT600 band plan release following a 3GPP Band 71 or APT600 FDD arrangement, from the early 2030s. The IMT SDL allocation would follow that described in the second scenario but relies on DTT spectrum being released by the transition of TV services to the IPTV platform, at a later date which could be in the late 2030s and assumes an eco-system of devices supporting such an IMT SDL band will have been established by that time.

As examined with the previous scenario, there would need to be reasonable confidence that an IMT600 FDD band plan can in principle co-exist with the DTT network and more importantly with DTT networks in the Republic of Ireland, France, the Netherlands and Belgium. These interference and co-existence risks were discussed in detail in the previous scenario for the scenario where IMT600 only is established.

As highlighted in the previous scenario also, France has the highest adoption of IPTV Households in Europe. There are 19.65M out of 31.63M households in France with IPTV service (62%), compared to 4.85M households with DTT service (15%)[51]. France is therefore best placed to progress to a transition to IPTV, and if France might be encouraged to pursue an all-IPTV future for its TV meaning there could be more appetite for France to explore an IMT600 route similar to this scenario being examined. If so, then coordination with the UK would be in the same interests, although coordination with Italy, and other countries may be less so.

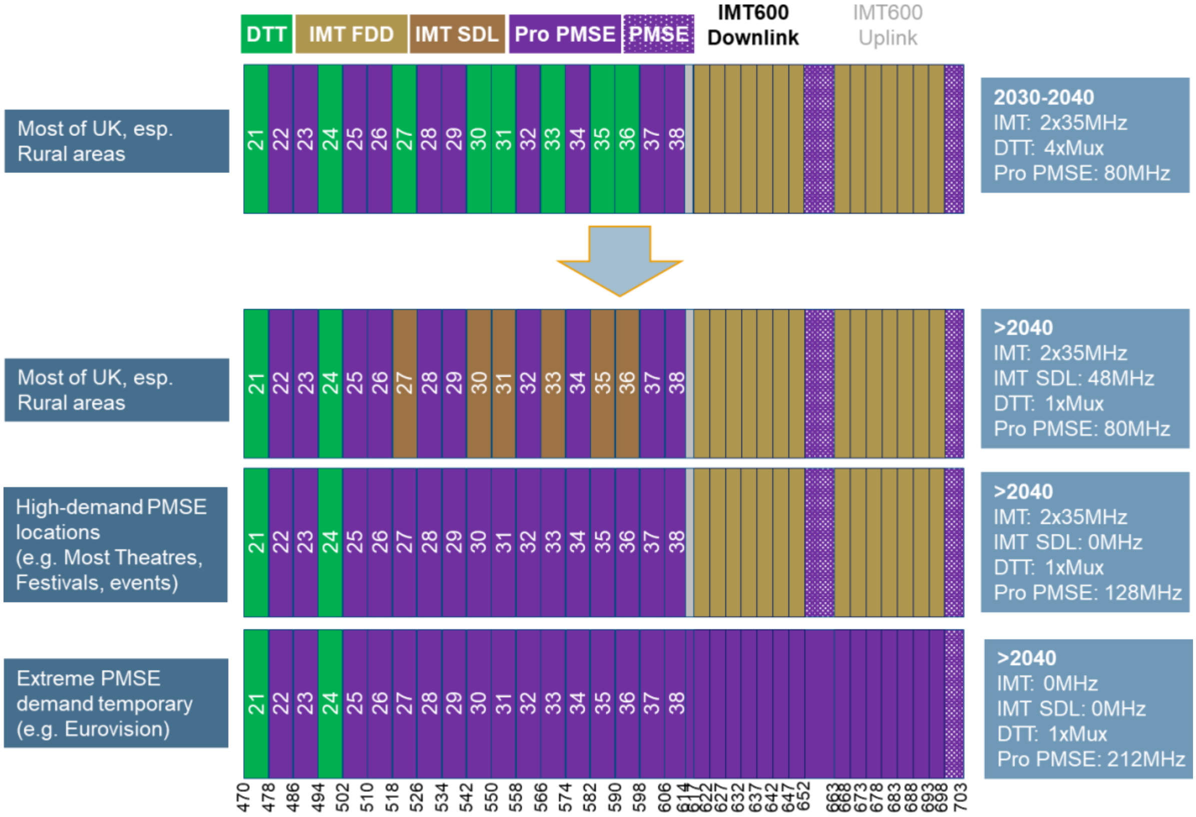
4.4.3 PMSE under transition of DTT to IPTV

The Exhibit below helps illustrate this scenario for IMT and PMSE use. Let’s assume that a location is served by two main broadcast DTT transmitters (such as York as used in a previous example), which in fact presents more of a worse-case situation for available interleaved spectrum for PMSE use. Referring to the top spectrum arrangement, this shows that eight DTT channels are occupied which would be four channels from each DTT Transmitter, representing the four DVB-T2 multiplexes. This spectrum allocation arrangement might be in place say during most of the 2030s, as IPTV has yet to replace DTT households in sufficient numbers. Also, this might mean around 80 MHz is available for professional

PMSE use and should be representative of locations and times where PMSE is not in any high demand, which is likely to be most of the UK landmass. Any peak PMSE demand (e.g., theatres, events, city centres, etc.) could use the 80 MHz spanning the IMT600 band plan under a shared licencing framework with MNOs as described in the previous scenario.

Sometime in the late 2030s or early 2040s, IMT SDL can be issued to MNOs and perhaps on a region-by-region basis as IMT SDL becomes available and our example is shown in the second spectrum arrangement in the Exhibit below. As the DTT platform can drop from four multiplexes to one multiplex, this releases six 8 MHz channels in this example location for use by IMT SDL. Because IMT SDL replaces DTT there is in principle no change in spectrum available for PMSE. The third spectrum arrangement depicts the case where PMSE needs additional spectrum perhaps in identified high demand areas such as some theatres, or urban centres. This sharing arrangement now allows MNOs to perhaps use more of their IMT600 FDD spectrum in urban areas too, and only sacrificing the IMT SDL spectrum component for PMSE. Finally, for the handful of extreme PMSE spectrum use cases, the final spectrum arrangement can be provided perhaps on a temporary basis in that location for the limited time the PMSE spectrum is required.

Exhibit 38: Co-primary and mobile split spectrum for transition to IPTV scenario – spectrum allocation examples



Source: Coleago Consulting

4.4.1 Other stakeholders for 470-694 MHz spectrum

We have been made aware that there is at least one other stakeholder seeking around 50 MHz of spectrum in the lower portion of 470-694 MHz. This has not been made publicly available at this time, and the details of where and when such spectrum would be used is not clear, although we expect a low usage characteristic.

If there is a longer-term transition to IPTV which enables more of the 470-694 MHz band to be freed up, then new stakeholders and applications could be more readily accommodated. In this case perhaps IMT SDL does not get traction then this provides an opportunity for new players and expansion of other services including IoT, PPDR, etc.

4.5 Summary of international regulatory implications for the scenarios

This section summarises the implications of the international regulatory framework on the four scenarios we have defined, focusing on decisions that could be made at the next three World Radio Conferences, WRC-23, WRC-27 or

WRC-30/31 since the scenarios trace the potential outcomes for DTT, Mobile Communications and PMSE from the early 2030s onwards.

A number of different regulatory decisions could be taken at these WRCs, however, in the Exhibit below we focus on the two outcomes we have already mentioned in our scenario analysis – "no change" and co-primary" for mobile and broadcasting. A study of the resilience of the scenarios to a wider range of international regulatory outcomes would undoubtedly be of value and could be a subject of further study, but it is beyond the scope of this report.

Exhibit 39: Implications of the international regulatory framework for the scenarios

Scenario	International Regulatory Outcome		Impact on Competing Services		
	No Change	Co-Primary	DTT	Mobile Comms.	PMSE
1: Status Quo	✓	✓ in the event no eco-system for IMT SDL emerges by early 2030s Otherwise ✗	Opportunity to deliver maximum (HD) content depending on end-user demand	May be capacity constrained esp. in rural areas depending on end-user demand and defragmenting 700/800/900	Possibility of more spectrum depending on growth in end-user DTT demand
2: Flexible Use	✗	✓ this is the embodiment of a Co-Primary outcome, where an eco-system for IMT SDL emerges by early 2030s	DTT reduces to 3-5 MUXes assuming end-user demand only supports existing payload	Spectrum dividend for IMT SDL; size depends on whether and how DTT network is upgraded	Minimum impact, no change in spectrum; coordination with IMT SDL could allow more spectrum with peak demand
3: IMT600 Band Plan	✗	✓ only if a "Primary" decision for IMT in 600MHz is made by WRC-30/31 (e.g. if IMT600 looks more promising compared to IMT SDL in the run up)	Possibility of more HDTV payload on 4-5 MUXes, but network re-design & upgrade has cost implications	Additional spectrum for IMT, but with requirement to coordinate to protect existing PMSE use	Coordination with IMT SDL could allow more spectrum with peak demand
4: Transition to IPTV	✗	✓ only if a "Primary" decision for IMT in 600MHz is made by WRC-30/31 (e.g. if IMT600 looks more promising compared to IMT SDL in the run up)	Technology enabled reduction to 4-5 MUXes in 2030s and 1-2 MUXes in 2040 if/when pivot to IPTV happens	Additional spectrum for IMT FDD in 2030s (PMSE coordination required) and for IMT SDL in 2040s from IPTV "spectrum dividend"	Coordination with IMT SDL could allow significant spectrum with peak demand; unaffected by IMT SDL use in 2040s

Source: Coleago Consulting

5. Potential Areas of Further Research

To identify which scenario will predominate we believe that the following topics will need further study:

- Assessment of potential DTT spectral efficiency improvements – technical and economic
- Assessment of impact of potential PMSE exclusion zones for IMT 600 – technical and economic
- Assessment of the potential use of other bands for PMSE – technical and economic
- Cost/benefit analysis for potential end-user PMSE equipment upgrade/swap – technical and economic
- Assessment of potential use of 5G Broadcast (5GB) technology – technical and economic
- Analysis of the potential business models for 5G PMSE and 5G Broadcast
- Assessment of MNO Low-Band spectrum defragmentation options capturing Trading, Carrier Aggregation Combos, PIM Interference risks and 4T4R Low-Band Radio architectures (for 4 x 4 MIMO).
- Analysis of co-channel interference risk to IMT600 Uplink from DTT stations located in France, Ireland, Netherlands, and Belgium. Conduct measurements and monitoring of non-UK DTT transmissions and analyse results for interference risks into IMT600 FDD Uplink.
- Analysis of IMT600 FDD uplink interference mitigation methods.
- Study of 2 x 40 MHz APT vs 2 x 35 MHz Band 71 IMT600 band plan for UK. Device support projections, IMT600 Downlink to DTT Receiver interference risk assessment.
- Cost and impact analysis to PMSE community with a UK IMT600 band plan adopted, assuming different levels of IMT/PMSE geographic coordination.
- Transition to IPTV study - examination of digital skills gaps and solutions, broadband infrastructure projections by region.
- Analysis of the resilience of scenarios to a wide range of international regulatory decision and assessment of the opportunity costs related to such decisions

Annex 1: Literature Search

Exhibit 40: Research table

Title	Author/organisation	Publication date
700 MHz Clearance Planning Options Based on Existing Usage	Mark Jordan & Karina Beeke for Arqiva	23/03/2012
Coexistance of DTT and Mobile Broadband: A Survey and Guidelines for Field Measurements	Wiley/Hindawi	2017
Connected Nations Update	Ofcom	Autumn 2022
Conductive Measurements of DTT Receiver Selectivity in Response to Interference from Adjacent Channel White Space Devices and LTE Mobiles	DTG Testing Ltd for Ofcom	11/10/2013
DACH: State of Mobile Networks	Fi Armstrong & Chris Mills for Tutela	07/2020
Digital UK's Response to the Ofcom Consultation: Coexistence of New Services in the 800 MHz Band with DTT	Digital UK	11/08/2011
EBU Eurovision Song Contest, Annex XX	-	-
Entertainment Technology Industry Research Report 2017/2018	Plasa	-
Ericsson Mobility Report Q2 2022	Ericsson	2022
Ericsson Mobility Report June 2022	Ericsson	2022
Fact Sheet: Amendment of Parts 14 & 74 of the Rules for Wireless Microphones in the TV Bands, 600 MHz Guard and 600 MHz Duplex Gap, and the 941.5 – 944 MHz & 944 – 952 MHz	Federal Communications Commission	01/04/2021
Film Forever: The UK Film Economy	BFI Research & Statistics Unit	-
Hybrid Meeting – PTD-7	CEPT/Electronic Communications Committee	18/08/2022
Low Latency 5G for Professional Audio Transmission (white paper)	Nokia/Sennheiser	-
Made Outside London Programme Titles Register 2021	Ofcom	17/08/2022
Media Nations 2022	Ofcom	17/08/2022
Media Reform Green Paper, Modernising Television Reform in Australia	Chris Smith for Seinnheiser Australia Pty Ltd	21/05/2021
Music Studio Market Assessment	Department of Digital, Culture, Media and Sport	06/2021
Ofcom and the London 2012 Olympic and Paralympic Games	Ofcom	18/12/2012
Online Nation 2022 Report	Ofcom	01/06/2022
Perspektiven Zur Nutzeng des UHF ands 470 – 694 MHz Nach 2020	Goldmedia GmbH, Fraunhofer IIS & Prof. Dr Jürgen Kühling L.L.M	18/11/2021
PMSE: Spectrum Sharing in the Time Domain	-	-
Report ITU-R BT 2301-3: National field reports on the introduction of IMT in the bands with co-primary allocation to the broadcasting and mobile services	International Telecommunications Union	03/2021
Spectrum Demand for Professional Wireless Production Tools (PMSE)	Georg Fischer & Thomas Ackermann for FAU University Press	2022
Stage Set for New London Film Studios	Louisa Clarence-Smith, Property Correspondent	01/04/2021
Suggested Broadcast and Digital Dividend Contacts	-	-
The Future Use of UHF Spectrum in the ITU Region 1	Tim Miller, Yi Shen Chan, Akhiljeet Kaur & Karim Bensassi-Nour for Plum	05/2021
The Viewing Report	BARB (Broadcasters' Audience Research Board)	06/2021

Title	Author/organisation	Publication date
Transition to Digital TV and Mobile Broadband: Impact on Wireless Mics and Solutions Adopted in the US	Joe Ciaudelli, Director for Spectrum Affairs, Sennheiser Research and Innovation	28/08/2017
Use, Locations and Economic Value of PMSE	-	-
Use of UHF Spectrum for Programme Making and Special Events in the UK (issue 1.5)	Mike Reynolds, Niall Mottram, Robert McHardy & Stella Wooder for Sagentia	13/12/2006
WRC-23/27 & Audio PSME	Brian Copsey (ASP), Duncan Bell (BEIRG) & Tuomo Tolonen (Shure)	11/2021
WRC-27 & the Audio PSME	Copsey Communications Consultants	11/2021

Source: Coleago Consulting

Annex 2: Stakeholder Interviews

In the preparation of this report, we have conducted a wide range of interviews with many of the key the stakeholders involved in the usage of the UHF spectrum and all interviews were conducted under Chatham House rules. in total 17 stakeholder organisations were interviewed including:

- Ofcom
- FCC (USA)
- BT/EE
- Three
- Virgin Media O2
- Nokia
- Copsey Communications Consultants
- Sennheiser
- Shure
- BEIRG
- BBC
- Digital 3&4
- DTG
- DMSL
- Rohde & Schwarz
- Qualcomm

Annex 3: Glossary

3GPP	3rd Generation Partnership Project
4K	Ultra-High-Definition TV standard ~4,000 horizontal pixel resolution
AI	Artificial Intelligence (i.e., machine learning).
ADSL	Asymmetric Digital Subscriber Line
APWPT	Association of Professional Wireless Production Technologies
API	Application Protocol Interface
APT	Asia Pacific Telecommunity
AR	Augmented Reality. Also see VR.
ARIMA	Auto Regressive Integrated Moving Average
ARPU	Average Revenue per Unit.
AUPU	Average Usage per Unit or per User
AV	Audio Visual
AVOD	Advertising-based Video-on-Demand/Advertising-financed Video on Demand
BBU	Baseband Unit.
BEM	Band Edge Mask
BNE	Broadcast Networks Europe
BVOD	Broadcaster Video-on-Demand
CA	Carrier Aggregation
CAGR	Compound Annual Growth Rate
Capex	Capital Expenditure (i.e. investments)
CEPT-ECC	Electronic Communications Committee of the European Conference of Postal and Telecommunications Administrations
C-PMSE	Cognitive Programme Making and Special Events
COTS	Commercial Off-The-Shelf.
CPRI	Common Public Radio Interface
CU	Central Unit.
DL	Downlink
DSL	Digital Subscriber Line
DSS	Dynamic Spectrum Sharing (allows bandwidth to be allocated between different technologies such as 4G and 5G).
DTT	Digital Terrestrial Television
DU	Distributed Unit(s).
DVB-HB	Digital Video Broadcasting - Home Broadcasting

DVB-I Digital video broadcasting - internet	Digital Video Broadcasting - Internet
DVB-T	Digital Video Broadcasting – Terrestrial
DVB-T2	Digital Video Broadcasting - Terrestrial 2nd generation
EB	Exabyte (also see ZB)
EBITDA	Earnings Before Interest, Tax, Depreciation and Amortisation.
EAO	European Audiovisual Observatory
EBU	European Broadcasting Union
EC	European Commission
EIRP	Effective Isotropic Radiated Power
eMBB	Enhanced Mobile Broadband
eMBMS	Enhanced Multimedia Broadcast Multicast Services
eMTC	Enhanced Machine Type Communications
EPG	Electronic Programme Guide
ERP	Effective Radiated Power
ETSI	European Telecommunications Standards Institute
EU	European Union
FDD	Frequency Division Duplex. In FDD mode, half of the bandwidth is allocated to uplink, half to downlink. Hence the notation 2x20 MHz for a 20 MHz 'paired' channel. Also see TDD.
FeMBMS	Further enhanced Multimedia Broadcast Multicast Services
FR1, FR2	Frequency Range 1 (bands below 6GHz) and Frequency Range 2 (millimetre waves).
FTA	Free To Air
FTV	Free-To-View
FVOD	Free Video on Demand
FWA	Fixed Wireless Access.
GE06	Geneva 2006 Conference and Agreement
HbbTV	Hybrid broadcast broadband TV
HD	High Definition
HDR	High Dynamic Range
HDTV	High-Definition Television
HEVC	High Efficiency Video Coding
HFR	High Frame Rate
HPHT	High Power, High Tower
IBB	Integrated Broadcast-Broadband system
IEM	In Ear Monitor
IMT	International Mobile Telecommunications

IoT	Internet of Things: machine-to-machine or "machine-type" communications via the Internet, mediated by fixed and/or wireless networks.
IP	Internet Protocol
IPTV	Internet Protocol Television
ITU	International Telecommunications Union
LLS	Lower Layer Split (in context of open RAN)
LPLT	Low Power, Low Tower
LTE	Long Term Evolution (4G)
M2M	Machine-to-Machine (see IoT)
Mbps or Mbit/s	Megabits per second (a measure of network throughput).
MIMO	Multiple Input / Multiple Output antenna system; e.g. 2T2R (meaning two transmit and 2 receiver antennas on the site), which is the base MIMO configuration for 4G and 5G, also referred to as "order 2" or "2x2" MIMO.
MIP	Mobile Infrastructure Project
mMIMO	Massive MIMO (typically 32x32 or 64x64 order MIMO)
MNO	Mobile Network Operator
MPEG	Motion Pictures Expert Group
MPEG2	Video encoding standard, MPEG2 was the second of several standards developed by the Moving Pictures Expert Group
MPEG4	Video encoding standard, MPEG4 was the fourth of several standards developed by the Moving Pictures Expert Group
MPMT	Medium Power, Medium Tower
NGMN	Next Generation Mobile Alliance
NSA	Non-Stand-Alone
OFDM	Orthogonal Frequency Division Multiplexing
Opex	Operating Expenditures (recurring or 'running' costs)
O-RAN	Open RAN Alliance (not to be confused with "Open RAN")
OTT	Over-The-Top
PB	Petabyte (also see ZB)
PC	Personal Computer
PIM	Passive Inter-Modulation (intermodulation distortion caused by passive components)
PMSE	Programme Making and Special Events
PPDR	Public Protection and Disaster Relief.
PSB	Public Service Broadcasting
PSM	Public Service Media

QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network. Includes radio sites and backhaul transmission (but not the core network).
RF	Radio Frequency (e.g. RF unit)
RIC	RAN Intelligent Controller
ROIC	Return On Invested Capital
ROM	Receive Only Mode
RRU	Remote Radio Unit.
SA	Stand-Alone.
SD	Standard Definition
SDR	Software Defined Radio.
SLA	Service Level Agreement
SMO	Shared Rural Network
SRN	Service Management & Orchestration
SVOD	Subscription Video on Demand
TB	Terabyte (also see ZB)
TDD	Time Division Duplex. Also see FDD. Spectrum in TDD mode allows for asymmetric allocation of uplink and downlink resources, yielding greater overall spectral efficiency.
TIP	Telecom Infra Project
TV	Television
TVOD	Transactional Video on Demand
UE	User Equipment
UHD	Ultra-High-Definition TV standard ~4,000 horizontal pixel resolution
UHF	Ultra-High Frequency (300MHz to 3GHz)
UL	Uplink
UP	User Plane (in context of network slicing)
uRLLC	Ultra-Reliable Low Latency Communications.
VHF	Very High Frequency (30MHz to 300MHz)
VOD	Video On Demand
VR	Virtual Reality. Also see AR
VVC	Versatile Video Coding
WACC	Weighted Average Cost of Capital.
WCG	Wide Colour Gamut
WMAS	Wireless Multichannel Audio Systems
WRC	World Radio Conference

ZB	Zettabyte, equivalent to 1000 EB (Exabytes), 1 million PB (Petabytes), 1 billion TB (Terabytes) and 1 trillion GBytes.