Study on UHF Band (694 – 960 MHz)

Report for the UK Spectrum Policy Forum

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LS telcom UK
18 King William Street
London
EC4N 7BP
UK
Tel: +44 (0) 20 3740 6470
Email: info@LStelcom.com
Internet: www.LStelcom.com

Contact person:
Mr. Saul Friedner
Tel: +44 (0) 7931 824500
Email: sfriedner@LStelcom.com

About LS telcom

LS telcom is the global leader in spectrum efficiency with customers in over 100 countries worldwide. In an increasingly connected world, we assure that all spectrum users achieve their radio communication objectives in the most optimal and cost-efficient way. We deliver technologies and services to national and international regulatory bodies, to mobile and broadcast operators, to transport, critical infrastructure, defense, PPDR and vertical markets. We optimize spectrum management and spectrum use and enable new business models such as the internet of things (IoT) and 5G.

About the UK Spectrum Policy Forum

Launched at the request of Government, the UK Spectrum Policy Forum is the industry sounding board to Government and Ofcom on future spectrum management and regulatory policy with a view to maximising the benefits of spectrum for the UK. The Forum is open to all organisations with an interest in using spectrum and has over 200 member organisations. A Steering Board performs the important function of ensuring the proper prioritisation and resourcing of our work.

The current members of the Steering Board are:

- Airbus Defence and Space
- Avanti
- BT
- Department for Digital, Culture, Media & Sport
- Digital UK
- Huawei
- Ofcom
- Plum Consulting
- QinetiQ
- Qualcomm
- Real Wireless
- Sky
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techUK facilitates the UK Spectrum Policy Forum. It represents the companies and technologies that are defining today the world we will live in tomorrow. More than 950 companies are members of techUK. Collectively they employ approximately 700,000 people, about half of all technology sector jobs in the UK. These companies range from leading FTSE 100 companies to new innovative start-ups.

Contents

1 Executive Summary

The UK Spectrum Policy Forum (SPF) has commissioned LS telcom to undertake a study on the practical feasibility of defragmentation of the UHF band 694 - 960 MHz. This report presents the details from the analysis and findings from the study and the following sections provide a summary of each of the key aspects.

Introduction and background

There is ongoing demand in all regions of the world for additional spectrum to be made available to serve growing mobile data traffic. Spectrum between 500 MHz and 1 GHz (so called sub 1 GHz spectrum) is highly valued and intensively used as these frequencies have the unique combination of being suitable for handheld devices whilst being able to propagate widely. These values have been reflected in the relatively high prices paid to operate mobile networks in this spectrum. Much of the sub 1 GHz spectrum has historically been allocated exclusively for broadcasting purposes. However, the increasing demand for mobile spectrum has resulted in the original 900 MHz 'GSM' band being augmented by the 800 MHz band and most recently from the decision at ITU-R WRC ‘12 allocated the 700 MHz band as primary mobile spectrum (with release in the UK planned for H2 2019[1]). This additional mobile spectrum has led to a commensurate loss of broadcasting spectrum which has been compensated by the improved efficiency of digital broadcasting technologies.

In turn, the precedent would suggest that a further ‘salami slicing’ of the UHF band below 694 MHz is the next target for more mobile spectrum sub 1 GHz (which aligns with current mobile industry spectrum policy). However, in light of the repeated demand and piecemeal re-distribution of bands in sub 1 GHz spectrum it became clear that a long-term spectrum policy was needed. In 2013, the Lamy Report[2] identified that linear TV viewing would remain a dominant platform for the foreseeable future and that DTT spectrum below 694 MHz should be protected until at least 2030 to ensure predictability and sustainability for broadcasters. Other users of the UHF band, operating in the gaps within and between broadcasting and mobile use include GSM-R (for safety critical rail use), PMSE (wireless microphones and programme making), Short Range Devices (SRD), Met Office radar and some Emergency Services.

Interest in the future of this spectrum has been recognised in a provisional WRC-2023 agenda item which aims to review the mobile and broadcasting requirements across the entire range from 470 MHz to 960 MHz. Specifically, this agenda item includes the need to: “consider possible regulatory actions in the frequency band 470-694 MHz in Region 1 on the basis of the review in accordance with Resolution 235”.

In 2017, Digital UK commissioned Aetha Consulting[3] to examine use of the UHF band to understand options that could increase efficient use of the band, potentially giving more certainty to both mobile operators and broadcasters for long term access to this spectrum. Aetha's report identified three band-plan options for the potential future use of UHF spectrum between 694 MHz and 960 MHz,

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[1] 700 MHz clearance programme timescale review, Ofcom, October 2017

[2] Results of the work of the High Level Group on the Future Use Of The UHF band (470-790 MHz), Pascal Lamy, 2013 /

[3] The defragmentation dividend, A more efficient use of the UHF band, Aetha Consulting, Nov 2017

which claim to provide increased flexibility for future mobile use, whilst protecting future broadcast use. Aetha identified a number of benefits in the proposed band-plan options, suggesting:

- Potential downlink capacity increases of between 25% and 70%, with the higher increases linked to use of TDD technology
- Availability of large contiguous spectrum blocks allowing improved 'future use'

Aetha noted that these potential benefits are contingent upon overcoming a number of technical, market and regulatory obstacles. In response, the Spectrum Policy Forum has commissioned this study to examine Aetha's options in more detail. Specifically, this study has been asked to:

- Look in more detail and respond to some of the suggestions within the Digital UK sponsored study (Aetha, Nov 2017) including the practical feasibility of migrating to a large FDD band, three TDD bands, or an all TDD plan, as well as to examine and evaluate some of the intermediate steps in more detail.
- Consider the practical issues, including gaining a deeper understanding of the possible technical advantages of FDD vs TDD in sub-1GHz, the consideration of impact on other existing uses in the band, the costs of migrating 4 existing UK networks and European/Global networks to new technologies and band-plans and the consequences for consumer devices.
- Consider issues around coordinated migration of 4 networks, including possible impact upon coverage reach, coordination between countries and the consequences if additional spectrum were not available to facilitate a transition period.
- Investigate the legal/regulatory aspects as well as impact to other users in the band e.g. GSM-R across Europe.

Key features of the band-plan options considered

A summary of Aetha's migration options are shown in the figure below. It shows blocks for mobile uplink (light coloured), mobile downlink (dark coloured), supplementary downlink (vertical or horizontal line pattern) and TDD (red). Other uses including guard bands, GSM-R, PMSE and SRDs are shown as yellow. The total mobile spectrum available in each option is also shown.

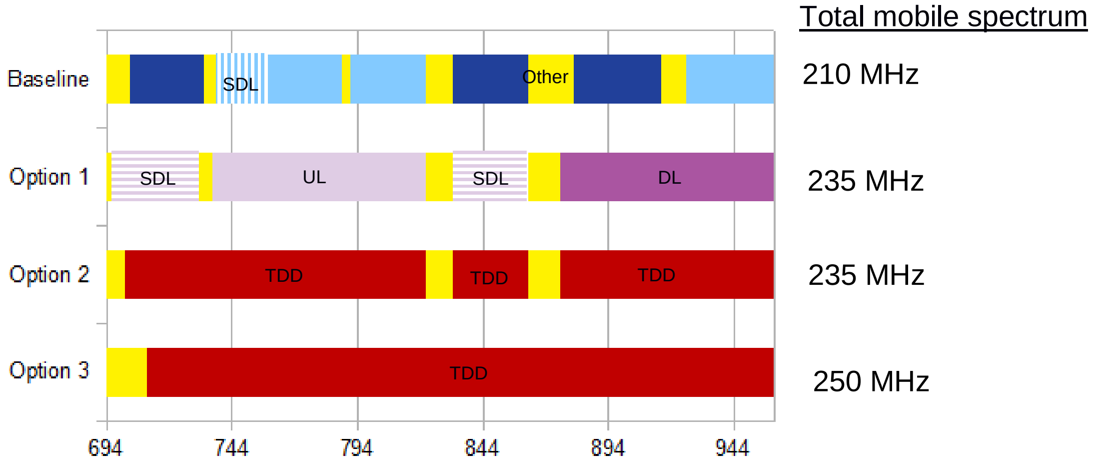

Figure 1: UHF band spectrum configurations baseline against three migration options

Baseline: This includes 3 MHz for M2M (733-736 MHz), a new European harmonised band for radio microphones (823-832 MHz), Police and Fire Service (862-863 MHz), and an augmented band for Licence Exempt SRD use (863-876 MHz). GSM-R uses 2x4 MHz of spectrum located just below the 900 MHz duplex bands (876-880 paired with 921-925 MHz).

Option 1: This includes two large and contiguous FDD blocks (2x85 MHz), supplemented by two downlink bands (1x30 and 1x35 MHz). 5 MHz of gaps and the designated 3 MHz for M2M (733-736 MHz) are reclaimed for mobile use. The harmonised radio microphone band (823-832 MHz) and 12/13 of the LE SRD band are retained.

Option 2: This comprises three TDD blocks (1x120 MHz, 1x30 MHz and 1x85 MHz). Similar to option 1, the harmonised radio microphone band (823-832 MHz) and 12/13 of the licence-exempt SRD band are retained.

Option 3: This comprises a single contiguous 250 MHz TDD band – achieved by removing access to other users of the band in the range 710 to 960 MHz. Other users of UHF spectrum (such as PMSE and SRD) are intended to be relocated to the 16 MHz gap between 694 and 710 MHz.

Mobile communications networks in 2030

This study has focused on the migration of mobile communication networks beyond 2030. There are numerous uncertainties in determining what a mobile network might look like in this timeframe, so using inputs from mobile operator stakeholders and research from 5GPPP projects we have determined a baseline configuration for a hypothetical operator in 2030.

Mobile communications capability is driven by the deployment of enabling techniques based on agreed harmonised standards that allow for scale development of equipment. The first 5G New Radio (5G NR) specification was completed in June 2018 and will be incorporated into Release 15 (and beyond) of the 3GPP standards and consumer products are expected approximately 1 year to 18 months later. In parallel, the 4th generation standard will continue to evolve and improve. Typically, a new mobile generation has emerged every ~10 years. By 2030, we anticipate that an early 6th generation system will start being introduced. This network will be able to flexibly support new technologies and multiple frequency bands including sub 1 GHz to deliver multi-service, multi-tenant network services to a wide geographical area with sufficient flexibility to serve congested areas and new services as they arise.

Feasible Migration Paths

The key to cost-effective mobile communications is to amortize development costs against a large addressable market, particularly with lower relative unit cost items such as handsets. This generally needs support of at least one ITU region and global harmonisation brings additional scale and roaming benefits. Hence a pre-requisite for this study is that any target migration end-points would already have established broad support within Europe, and probably Africa and possibly parts of ITU Region 3 (Asia Pacific).

That minimum buy-in would only occur if the migration and the end-point would offer cost and performance benefits. However, despite regional buy-in, it is assumed that handset chipset suppliers will not provide more than the minimum capability needed to satisfy standard 3GPP bands, and the end-point band-plan (i.e. equipment will not accommodate any other duplex/channelisation arrangement than the post 700 and end-point band-plan). Thus new devices would need to be developed to support both the baseline and end points for the preferred option during migration. We have assumed that bands are handled on a piecemeal basis so that all operators can always maintain operation in sub-1 GHz spectrum.

As a result of improved spectrum efficiency in higher frequencies, MMIMO, carrier aggregation and densification of small cells, we anticipate that the sub-1GHz spectrum capacity will support a small fraction (approximately 2%) of the total downlink capacity available to network operators by 2030 (see Annex B for more details).

Given all this, we have developed technical migration roadmaps for each of the options.

Option 1 (maximum FDD): This is constrained by needing to migrate multiple duplex bands to other duplex bands, with incompatible duplex gap and channel bandwidths. This results in access to a given part of the destination band-plan potentially needing access to (part of) the duplex frequencies of existing bands. This results in a loss of mobile spectrum during the migration.

Option 2 (TDD retaining many existing users): This option offers most flexibility in timing and migration with little dependence on when existing 3GPP bands are migrated.

Option 3 (TDD, moving all existing users): This option results in the largest amount of sub-1 GHz mobile spectrum in one large contiguous TDD block. This option retains many of the benefits of Option 2, but needs to accommodate migration of all existing users which results in loss of access to spectrum during the migration.

Practical and technical constraints

Typically, cell range is uplink limited and since the handset transmit power limit is the same for either duplex mode, and TDD uplink is only active for a fraction of the time (we have assumed 20% in assessing TDD capacity gain). TDD handsets transmit less average power. Methods exist to compensate for power constrained transmitters (coding options), however a key benefit of LTE (and anticipated future standards) is the commonality of the transmission format used for both FDD and TDD equipment[4]. It would seem unreasonable to allow TDD to utilise more coding options than FDD and so we assume that TDD options would have less range than FDD. FDD will have less downlink capacity, but better reach (including outdoor to indoor coverage).

Another practical constraint is that the maximum electromagnetic radiation emissions from a single site cannot exceed the international (translated into national) limits in accordance with ICNIRP[5] guidelines. It is difficult to specify the exact consequence of migrating to any of the given options, based on emission limits, since different sites will have different considerations and capacity limits, we can make the following general observations:

- Sub 1 GHz carriers will typically have greater power density than others (say, 4W / MHz), whereas other carriers up to 3 GHz more typically would use 2W / MHz.
- For the same transmitted power, ICNIRP guidelines consider radiated power below 1 GHz to be more damaging than above 2 GHz. The aggregated relative weighting across all bands is used to assess proximity to the maximum limit.

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[4] Signals Research Group white paper for Ericsson and Qualcomm: The LTE standard - Developed by a global community to support paired and unpaired spectrum deployments. April 2014.

[5] ICNIRP guidelines for base stations https://www.icnirp.org/en/applications/base-stations/index.html

- Subject to performance targets, each operator would seek to reduce the number of sites used, and to maximise the benefits of sharing (potential sharing gains are likely to be increased with 5G and beyond).
- Increased sharing and use of sites to support multiple bands (as anticipated) will increase the RF exposure levels from those sites.
- Sites that are already close to ICNIRP limits may make future upgrades more challenging.

Clearly increasing the amount of spectrum used to transmit from a site (including use of sub 1 GHz TDD) would bring any site closer to the maximum guidelines. ICNIRP guidelines do not address beamforming antennas which will provide capacity benefits in mmWave bands. Based on reasonable assumptions, for the same radiation exposure increase, approximately 10 times the data throughput can be achieved at mmWave bands than in sub 1 GHz bands. Therefore any operator close to the ICNIRP limit would consider this as part of their deployment strategy.

We observed that because of the impact to other users in the band in particular GSM-R, SRDs and PMSE users, Option 3 would be the most challenging and costly. However, there would need to be considerations for not just harmonised use of these bands but also interoperability and knock on effects to the (temporary) loss of benefits of the sectors and industries that depend on access to this spectrum and the related costs. These include aspects such as network and infrastructure upgrades for IoT, re-planning of GSM-R/FRMCS and PMSE equipment. We did not examine the costs of moving these other services in the band but the costs to migrate them will be in addition to the costs for mobile operators. It could be argued that new networks for rail and low latency, ultra reliable communications (e.g. smart meter and other IoT) and the associated costs become part of the mobile upgrades to future 5G networks.

Commercial constraints

We found that a migration to options 2 and 3 have similar network infrastructure costs but are likely to be more expensive to deliver compared to option 1. The key driver for the cost is the need to perform changes on every single macro site, not just those needing a capacity increase or periodic servicing. The main cost elements are multiple site visits with associated commissioning and testing, antenna panel replacement, RF front ends, feeders and combiners. In some cases, the mast at the sites may need to be strengthened to support new heavier antennas. This requires additional design and structures and could result in complete rebuild/replacement of the site.

We also found there are challenges and often large costs to re-negotiate terms with landlords of sites. It can also be time consuming to make the smallest of changes and multiple changes and visits may not be efficient or practical from a network operations perspective. Necessitating change at every macro-site location is therefore challenging under existing planning and roll-out conditions.

Legal and regulatory aspects

Defragmentation of the sub 1 GHz band would be possible under the current regulatory framework. To allow users and operators to access larger contiguous frequencies, it is necessary to re-allocate (change the use in some portions of the bands to and from mobile, depending on the current use and the chosen defragmentation scenario) and re-assign (vary the licenses and licence exempt instruments to shuffle the users and operators in a way in which they can access portions of the spectrum that are larger and consecutive). Any re-allocation or re-assignment will need to go through one or more public consultation procedures to create consensus within the mobile industry but also rail, SRD and PMSE sectors.

Conclusion

Overall our study has found that the migration options, albeit technically feasible, would require multiple site visits to every macrocell site in the network. This drives costs. We also do not foresee any regulatory challenges that could not be addressed by standard measures.

Migration to any of these options would require buy-in and complete support of the existing licensees - the mobile operators. By 2030 operators are likely to have other, probably lower cost, methods of improving capacity that will not suffer the potential practical constraints of sub 1GHz TDD or require re-engineering every site in the network. We believe that network operators should be consulted to assess if they believe the potential benefits outweigh the costs.

2 Introduction

2.1 Background to the study

There is ongoing demand in all regions of the world for additional spectrum to be made available to serve growing mobile data traffic. Spectrum between 500 MHz and 1 GHz (so called sub 1 GHz spectrum) is highly valued and intensively used as these frequencies have the unique combination of being suitable for handheld devices whilst being able to propagate widely. These values have been reflected in the relatively high prices paid to operate mobile networks in this spectrum. Much of the sub 1 GHz spectrum has historically been allocated exclusively for broadcasting purposes. However, the increasing demand for mobile spectrum has resulted in the original 900 MHz 'GSM' band being augmented by the 800 MHz band and most recently from the decision at ITU-R WRC ‘12 allocated the 700 MHz band as primary mobile spectrum (with release in the UK planned for H2 2019[6]). This additional mobile spectrum has led to a commensurate loss of broadcasting spectrum which has been compensated by the improved efficiency of digital broadcasting technologies.

In turn, the precedent would suggest that a further ‘salami slicing’ of the UHF band below 694 MHz is the next target for more mobile spectrum sub 1 GHz (which aligns with current mobile industry spectrum policy). However, in light of the repeated demand and piecemeal re-distribution of bands in sub 1 GHz spectrum it became clear that a long-term spectrum policy was needed. In 2013, the Lamy Report[7] identified that linear TV viewing would remain a dominant platform for the foreseeable future and that DTT spectrum below 694 MHz should be protected until at least 2030 to ensure predictability and sustainability for broadcasters. Other users of the UHF band, operating in the gaps within and between broadcasting and mobile use include GSM-R (for safety critical rail use), PMSE (wireless microphones and programme making), Short Range Devices (SRD), Met Office radar and some Emergency Services.

In a report produced by Aetha Consulting on behalf of Digital UK a new solution for delivering more capacity for mobile operators was conceived. It determined that defragmenting the entire 694 – 960 MHz band could add more capacity sub 1 GHz, instead of mobile operators seeking to obtain more spectrum below 694 MHz (as has happened recently in the United States of America). The Aetha proposal also has the potential of benefiting mobile services whilst protecting broadcasters.

The Aetha report took a long-term view of defragmentation of the UHF band below 1 GHz to support efficient future use and safe-guard DTT beyond 2030. A key driver is that successive piecemeal allocation has resulted in fragmented blocks of spectrum which are at odds with the higher contiguous bandwidths needed to (efficiently) support emerging and future communications standards (including 5G).

This study intended to dig deeper into the proposed options and issues discussed in the Aetha report and provide some insight into the practical issues, technical constraints and other implications for undertaking a migration of the mobile networks in the UK.

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[6] 700 MHz clearance programme timescale review, Ofcom, October 2017

[7] Results of the work of the High Level Group on the Future Use Of The UHF band (470-790 MHz), Pascal Lamy, 2013

2.2 Key features of the band-plan options considered

We consider Aetha's three main band-plan options which are shown in Figure 2 and have the following key attributes:

Baseline: This is the anticipated spectrum use post the 700 MHz spectrum release – consisting of 210 MHz of mobile spectrum. This includes 3 MHz for M2M (733-736 MHz), a new European harmonised band for radio microphones (823-832 MHz), Police and Fire Service (862-863 MHz), and an augmented band for Licence Exempt SRD use (863-876 MHz). Other gaps without such clear use amount to a further 8 MHz. Presently GSM-R uses 2x4 MHz of spectrum located just below the 900 MHz duplex bands (876-880 MHz paired with 921-925 MHz). Dedicated spectrum for GSM-R is not accommodated in other options.

Option 1 facilitates 235 MHz of mobile spectrum (with 2 large and contiguous FDD blocks (2x85 MHz), supplemented by two downlink bands (1x30 and 1x35 MHz)). 5 MHz of gaps and the designated 3 MHz for M2M (733-736 MHz) are reclaimed for mobile use. The harmonised radio microphone band (823-832 MHz) and 12/13 of the LE SRD band are retained.

Option 2 consists of a total of 235 MHz of mobile spectrum, with 3 TDD blocks (1x120 MHz, 1x30 MHz and 1x85 MHz). Similar to option 1, the harmonised radio microphone band (823-832 MHz) and 12/13 of the LE SRD band are retained.

Option 3 consists of a contiguous 250 MHz TDD band – achieved by removing access to other users of the band in the range 710 to 960 MHz. Other users of UHF spectrum (such as PMSE and SRD) are intended to be relocated to the 16 MHz gap between 694 and 710 MHz.

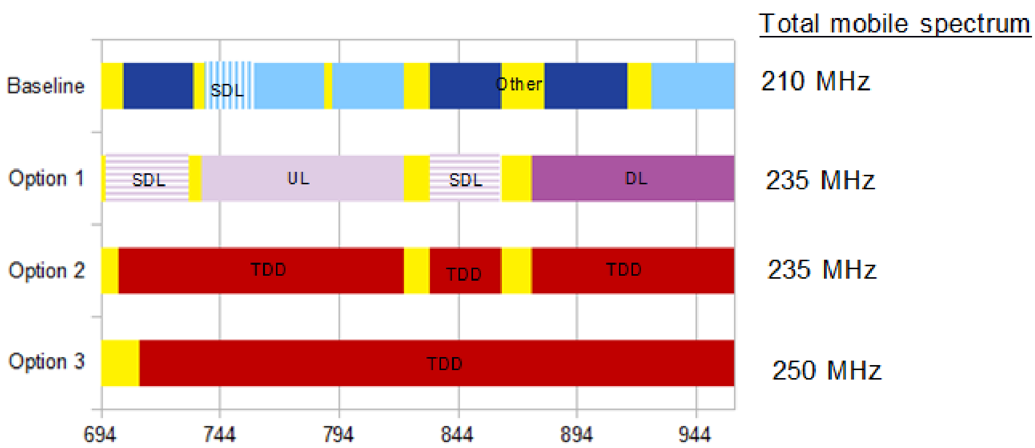

Figure 2: Band-plan options developed by Aetha Consulting

2.3 Purpose of the study – problem statement

Specifically, the purpose of this study is to:

- look in more detail and respond to some of the suggestions within the Digital UK sponsored study (Aetha, Nov 2017) - including the practical feasibility of migrating to a large FDD band, three TDD bands, or an all TDD plan, as well as to examine and evaluate some of the intermediate steps in more detail.

- consider the practical issues, including gaining a deeper understanding of the possible technical advantages of FDD vs TDD in sub-1GHz, the consideration of impact on other existing uses in the band, the costs of migrating 4 existing UK networks and European/Global networks to new technologies and band-plans and the consequences for consumer devices.
- consider issues around coordinated migration of 4 networks, including possible impact upon coverage reach, coordination between countries and the consequences if additional spectrum were not available to facilitate a transition period.
- investigate the legal/regulatory aspects as well as impact to other users in the band e.g. GSM-R across Europe.

At first glance the proposals seem to advocate significant change, including use of new not-yet harmonised spectrum that is not compatible with legacy frequency plans. In turn, this presents some major challenges, including:

- **Equipment Availability/Harmonisation**: Use of equipment (base station and handsets) operating in harmonised bands is a pre-requisite for cost-efficient infrastructure. The work cannot be done in isolation by the UK and needs to be done (at least) to a European scale but preferably at an ITU/regional scale.
- **Practical Migration**: Mobile networks will need to maintain service continuity during any transition. This means that there needs to be a mechanism to allow temporary solutions as well as the intended final plan. This will result in costs in equipment and configuration overhead as well as some temporary capacity loss which is commercially damaging for MNOs.
- **Spectrum Holding:** Operator's spectrum portfolios have been assembled over time and, in some ways, the propagation characteristics are complimentary. Re-assignment risks operators losing this complementarity or sacrificing 'clean' spectrum for spectrum with a 'noisy' neighbour would be unwelcome. All operators would seek an improvement both in absolute terms and would not want to lose any competitive advantage to an operator with a less attractive holding. This is likely to be highly sensitive. Re-writing of the UHF band-plan, particularly in any transition period, requires operator co-operation and a degree of flexibility.
- **Regulatory Considerations**: Cooperation between operators will be key particularly in the case of TDD deployments. Changes to licences and technical conditions will need to be considered both in terms of licensing and competition aspects. The technical conditions of different licenses (e.g. duplex direction, power constraints in rent regions, border co-ordination) and who is able to own/use spectrum is likely to vary from the status quo, and during any transition period. Regulators in different countries have different conditions and views on what is required to motivate sufficient competition. Any transition plan must be cognisant of these issues.

The above challenges are not trivial and operators are continually cost constrained particularly outside of business as usual activities. However, unless the implications are examined in more detail a decision cannot be on whether this may present an opportunity to reduce costs and deliver more efficient use of spectrum.

Whilst there may be downlink capacity benefits in adopting TDD, any change would be occurring at a time when the industry will be transitioning technologically and potentially with different business structures (facilitated by 5G). The key to realising any UHF defragmentation dividend is to ensure that the UHF transition can be accommodated as part of an inevitable change in business structure. Regulators may also be more flexible since they also recognise the business challenges being faced by operators compared to some times in the past and the benefits to society of having spectrum being used efficiently. Therefore, the outcome of this study will help industry and policy makers understand the issues and practical feasibility of migration and provide some further detail which may support decisions by government and/or industry to consider and conduct further work in this area.

2.4 Structure of the document

This document is structured as follows:

Chapter 2 Introduction – This section covers the background and purpose of the study

Chapter 3 Future Mobile network capability – This section provides an overview of the future mobile technology evolution for 2030, the type of mobile sites that will evolve and the practical constraints that arise for operators given the proposed migration.

Chapter 4 Feasible migration paths – This section covers the step-by-step approach to undertaking each of the migration options including the impact to mobile and other users in the UHF band

Chapter 5 Relevant legal and regulatory considerations – This section discusses the main considerations from a legal and regulatory perspective focusing on the required changes to spectrum allocation and assignment

Chapter 6 Summary of findings – This section provides an overview of the study findings

Chapter 7 Conclusions and recommendations – This section provides the conclusions and a set of recommendations for SPF to use and take to Government and Ofcom

3 Future mobile network capability

3.1 Future mobile services in the UHF band

Visions for future mobile services around the timeframe of interest (2030) will be based upon the evolution of 5G and 5G-NR (New Radio). The 5G vision is to provide a network[8] that can "efficiently connect virtually everything". 3GPP Release 15 will be the first 5G NR standard, and is scheduled to be frozen by Q3 2018[9], with equipment roll-out anticipated as early as 2019. In practice, wide scale deployment and use can be expected 2-5 years after that, and additional functionality will be incorporated as the standards evolve. We should note that LTE nominal peak data rates have increased by a factor of 30 between Release 8 and Release 14 (100Mbps to 3000Mbps).

The 5th generation mobile network is expected to provide the following key benefits:

- Improved performance, reduced costs and reduced energy use
- One network ("A unifying connectivity fabric") supporting many different services and user types – virtually everywhere. Services will span a wide range of connection capabilities - from enhanced Mobile Broadband (eMBB), massive Machine-Machine communication (mMMC) to Ultra-reliable Critical Machine Communication (URLLC).
- Ability to utilise a wide range of spectrum sub 1-GHz (as an anchor/coverage layer), 1-6GHz for wider bandwidths (eMBB, and mission critical) and mmWave bands (>24GHz) for extreme bandwidths) and spectrum types (licensed, shared, and unlicensed)[10]. Spectrum will be able to be utilised when it is available for use (building on existing aggregation methods)

In addition, networks will better support a range of different deployment types to integrate the different bands, base-station sizes and connectivity modes, with improved automatic network (re-)configuration. This will help each operator to utilise available infrastructure assets. Furthermore, other architecture methods are being researched (e.g. 5G NORMA) and trialled to simplify how operators can support multi-tenant, multi-service network infrastructure using generic computer-server hardware, improve sharing and reduce network hardware and operational costs.

A further vision of 5G is to ensure that this "connectivity fabric" is available everywhere. Within the UK, Ofcom is reviewing coverage obligations with the aim of increasing mobile coverage.

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[8] Making 5G a reality: Addressing the strong mobile broadband demand in 2019 & beyond. Joint Qualcomm and Nokia white paper. September 2017.

[9] http://www.3gpp.org/release-15. Accessed 3rd May 2018.

[10] It is noted that operators will seek to use sufficient UHF spectrum to provide the anchor/coverage layer, but that higher capacity throughput will be more efficiently supported in higher frequencies. Hence after the rollout of the 700MHz band, we anticipate MNO's priority will be in higher frequency spectrum (including the mmWave band). This is consistent with Ofcom's observation in its report on public service broadcasting in the digital age (https://www.ofcom.org.uk/__data/assets/pdf_file/0026/111896/Public-service-broadcasting-in-the-digital-age.pdf) earlier work had suggested that there would be strong competition from mobile companies for the valuable airwaves, or spectrum, that underpin DTT. But mobile demand has substantially diminished as investments in 5G require spectrum at higher frequencies.

In turn, Ofcom[11] has identified three coverage obligations which intend to improve coverage to rural areas and premises and an obligation to deliver 92% geographic coverage. Therefore, by 2030 we would expect 4G/5G coverage to be extensive (>92% of the UK landmass) across the UK.

Thus, the sub-1 GHz spectrum is key to providing a wide area coverage layer. This layer will be able to provide extended (both geographically and to provide outdoor-indoor) coverage and control to integrate other infrastructure to provide service (integrating use of other spectrum and small cells, etc).

Given these aims, the types of future mobile services, of particular relevance to the sub 1-GHz band will include:

- Significantly improved indoor mobile service penetration for 4G/5G MBB
- IoT and M2M including smart meters, PPDR type services outdoor eMBB
- V2X communications 100% of Strategic Road Network and connectivity to trains across all major rail routes

3.2 Technology evolution

The Aetha study identifies how capacity enhancements can be gained from technology evolution (e.g. MIMO) and deployment of more infrastructure such as small cells. Similarly, we note that many 5G research reports such as METIS, METIS II[12], 5G NORMA[13] and 5G MONARCH[14] indicate that technology evolution including massive MIMO, massive carrier aggregation and enhanced coding will deliver significant improvements in capacity and would expect operators to adopt some or all of these technologies over the next 10-12 years.

The key drivers for improved data throughput are to use more spectrum, to increase the densification of cell sites and to use multiple antenna methods that allow the same spectrum to be effectively re-used within the same sector – often multiple times. In addition spectrum efficiency will improve. These evolutions are discussed in the following sections.

3.2.1 Multiple antenna methods - MIMO and massive MIMO

MIMO techniques allow deployment of multiple antennas at a site to allow simultaneous re-use of spectrum to support several concurrent transmission channels between the transmitter and receiver. Channel conditions, and knowledge of them, and the number of antenna elements available limit the benefit of MIMO techniques. A key benefit of TDD is that the same frequency and channel conditions are presented for uplink and downlink directions. Therefore the base station can assess the channel condition with limited overhead having precise knowledge of the channel conditions. With FDD, the overhead in gaining information of the different uplink and downlink directions limits the number of

[11] Improving mobile coverage: Proposals for coverage obligations in the award of the 700 MHz spectrum band, March 2018

[12] https://5g-ppp.eu/metis-ii/

[13] https://5g-ppp.eu/5g-norma/

[14] https://5g-ppp.eu/5g-monarch/

practical antenna elements to approximately 4. Massive MIMO (with 32, 64 or even 128 elements) can be used with higher frequencies (between 3 and 6GHz), with mmWaves supporting even more antenna elements.

Owing to the limited physical size of antennas, massive MIMO is only practically possible and most efficient in spectrum above 3 GHz. In 5G NORMA for example, it states medium band of 3.4 -3.6 GHz bands support up to 32 element massive MIMO. Therefore, in sub 1 GHz bands the highest possible MIMO configuration could be 4x4 but most likely to be 4x2 which would be 4 transmit and 2 receive antennas. In sub-1 GHz bands, therefore, a key benefit of TDD technology (MMIMO) is not relevant.

3.2.2 Using more spectrum - Massive carrier aggregation

In order to use more spectrum in existing bands, a recent trend has been to aggregate the simultaneous use of multiple mobile bands. The trend towards increased aggregation and use of different spectrum has been increased in each recent spectrum release. Figure 3 shows the number of carriers that are defined in release 10 to Release 14 of 3GPP 36.101[15].This includes different combinations of carriers that can be aggregated to support higher bandwidth communications. LTE-A (Release 10) defined UE support for up to 5 component carriers so as to allow a maximum bandwidth of 100 MHz. Release 12 supports aggregation of a mix of TDD and FDD carriers; the TDD carriers do not need to support the same frame configuration. In practice the number of carriers that can be aggregated is limited by the combinations of bands supported, the base station capability (only 2 in Release 10) and the capability of the mobile being used. In time, these constraints will reduce.

In relation to this study spectrum aggregation provides key benefits for the flexible use of spectrum resources and enables enhanced capacity and performance with minimal cost. Benefits may include:

- aggregate component carriers in licence-exempt (or even shared) spectrum to boost the total bandwidth available – whilst using their licensed spectrum for control information and to maintain QoS
- improve the quality of experience for the users served (any one user can achieve a higher peak data rate, even if the total capacity delivered on the set of carriers may be the same)
- Allow a higher bandwidth to be available to support service and higher data rates than in any one carrier component.

3GPP Release 14 (March 2018) specifies a total of 386 carrier aggregation combinations for intra-band (contiguous carriers and non-contiguous with two sub-blocks), inter-band (selected 2-band, 3-band, 4-band and 5-band combinations). The growth in the number of supported combinations per release is shown in Figure 3.

[15] 3GPP 36.101 ETSI TS 136 101 V14.3.0 (2017-04) LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (3GPP TS 36.101 version 14.3.0 Release 14)

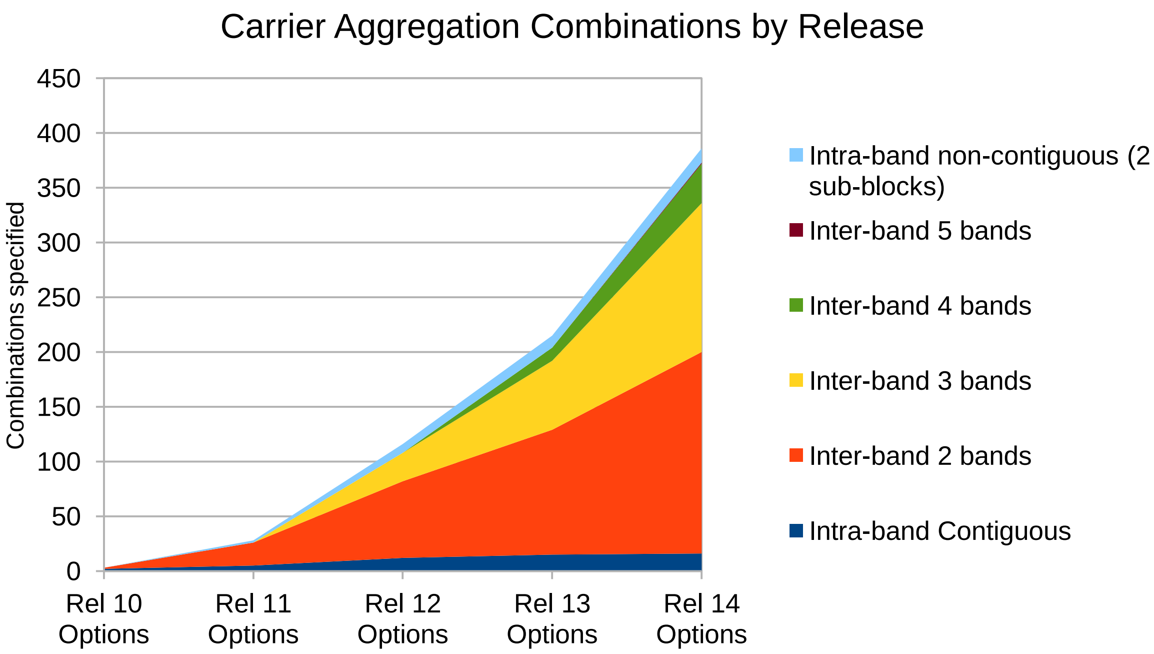

Figure 3: Carrier aggregation by 3GPP release

There is no reason to expect the number of bands that can be aggregated to reduce. There is a control overhead in aggregating spectrum, but this does not appear to be a significant barrier and sophisticated co-ordination of multiple base stations is a key enabling characteristic of some 5G performance improvements. Currently only high capability handsets can aggregate up to 5 carriers, but this is not expected to be a significant constraint by 2030. For practical purposes, we can assume that an operator will be able to aggregate any available blocks of spectrum that are available in order to support service, even if these blocks are not contiguous or in the same spectrum band.

3.2.3 Spectrum efficiency

The spectrum efficiency of TDD is typically approximately 10% more than for FDD, and this will be used in assessing relative downlink throughput in this document. In addition to MMIMO and using more spectrum, improvements are still being developed to improve utilisation of the communication channel, despite already being close to the Shannon limit[16].

For example, Nokia[17], claim that lean carrier, enhanced inter-cell interference cancellation and improved spectrum use will enhance 5G spectrum efficiency by a factor of approximately 1.6 compared to LTE. Qualcomm claim[18] that new large block coding methods can essentially double spectrum efficiency for mobile broadband traffic (compared to LTE Turbo codes), and others exist to

[16] The Shannon limit dictates the maximum throughput that any channel can carry based on the channel's physical characteristics.

[17] Nokia white paper: 5G New Radio: Technology and performance. July 2017.

[18] Qualcomm white paper: Making 5G NR a reality. December 2016.

improve control message transfer. These are being integrated into 5G NR and will improve performance in any spectrum band.

Against this, integrating many different services, with different latency and service delivery guarantee requirements complicates how traffic will be scheduled and will necessarily require reserved capacity and impose other overheads. However, it seems reasonable to anticipate that 5G NR will be able to deliver spectrum efficiencies in the sub-1 GHz spectrum between 2x and 3x existing values.

3.3 Site evolution

3.3.1 Antenna requirements at sub 1 GHz

In sub 1 GHz frequencies there are the physical and practical considerations for the antennas. For example, we found that:

- Single sector antenna 600- 800 MHz is 8ft high (2.5-3m) up to 50 kg with mounting kit (x3 for full omni-directional coverage)
- There is currently a limit to the number of ports available to support multi-operator although this will evolve over time
- 4x4 MIMO will be the limit for sub GHz frequencies (or 2x4)
- Current designs support FDD arrangement, redesign may be needed for TDD at sub 1 GHz
- The total number of antennas that can be deployed at existing location will be limited for a number of reasons, these include:
- Delays and often lengthy timescales for planning permissions – this is changing through updates to the Electronic Communications Code
- Commercial rent agreements between MNOs and landlords – landlords see any form of change to the site as a mechanism to charge more money – increasing costs
- Current limited capability and experience to support multi operator (x4) in sub GHz range
- Infrastructure design considerations such as loading of the mast with larger antennas, likely to be heavier due more sectors

We found that antennas are available that support the full 698 – 960 MHz band i.e. sufficient to support new RF front ends and tuning across the entire band. However, the site architecture and design and the number of different front ends needed is as yet unknown.

In order to understand further the technical limitations of antennas today, we examined a white paper from Kathrein[19] 'which indicates the following technical performance expectations:

- Sub 1500 MHz, MIMO performance likely to be 2x2
- Very high relative bandwidth antennas now feasible (>50% in 554-960 MHz)
- Splitting transmit and receive across different bands likely to be feasible

[19] Antenna Evolution – from 4G to 5G, Kathrein https://www.slideshare.net/KarvaCarbi/antenna-evolution-from-4g-to-5g-70581361

- Multi-band support with ~10's of antenna ports becoming 'normalised'
- Multi-operator sharing support of each antenna possible. Transmit power of ~900W per panel.

Given the above, we therefore assume that antennas will not constrain a band-plan that may otherwise bring benefits.

3.3.2 Feeders, couplers, combiners and mast head amplifiers

In addition to the antennas that will need to be upgraded to support the new 700 MHz band-plan, the feeders, coupler, combiners and mast head amplifiers will also need to be upgrade or swapped out if there is a migration of the UHF band.

We would assume, however, that these components would not impose any constraints on the network upgrade since these are high volume low cost components and would be available to support a migration within the timescales.

3.4 Constraints on spectrum migration within the UHF band

3.4.1 ICNIRP – Safe emission levels

ICNIRP is the formally recognized nongovernmental organization in non ionising radiation protection for the World Health Organization (WHO), the International Labour Organization (ILO), the European Union (EU) and other organisations. It is common practice in the mobile industry to verify that the maximum transmit power across all radio frequencies used does not exceed the limits identified in ICNIRP guidelines[20].

As more spectrum is deployed, and assuming more spectrum is used in the downlink direction (using TDD), it is useful to assess if typical deployments are likely to pose any significant change in the radiation exposure levels.

Whilst it is difficult to specify the impact of migrating to any of the given options since different sites will have different considerations and capacity limits, we can make the following general observations:

- Sub 1 GHz carriers will typically have greater power density than others (say, 4W / MHz), whereas other carriers up to 3GHz more typically would use 2W / MHz.
- For the same transmitted power, ICNIRP guidelines consider radiated power below 1 GHz to be more damaging than above 2GHz. The aggregated relative weighting across all bands is used to assess proximity to the maximum limit.
- Subject to meeting performance targets, each operator would seek to reduce the number of sites used, and to maximise and benefits of sharing (potential sharing gains are likely to be increased with 5G and beyond).
- Increased sharing and use of sites to support multiple bands (as anticipated) will increase the exposure levels from those sites.

[20] ICNIRP Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz). Health Physics 74(4): 494-522. 1998

- Using TDD (to increase downlink capacity) will increase the average base station transmit power compared to FDD
- Some existing sites are already close to ICNIRP limits and some operators are reportedly concerned that deploying mmWave spectrum may require care to avoid exceeding the limits.

Any detailed assessment of radiation levels would need to take into account idiosyncrasies of a particular location, antenna orientation, tilt, radiation pattern and the power level in each. However, we can assess the 'emission impact' of deploying further sub-1GHz spectrum to mmWave spectrum and the anticipated capacity gains. If close to the ICNIRP limits, and assuming sufficient capability in the anchor / coverage layer, a rational operator would choose the capacity maximising option that can be deployed at a given site. ICNIRP guidelines do not currently consider the impact of beamforming, and so some approximations will be made in this estimation process.

Assuming that each beam of the MMIMO array has equal power, and that a user is only exposed to one beam at a time, then, based on the assumptions of Table 1, for the same increase in exposure a 3.6 GHz MIMO beamformer can support 10.25 times that capacity as can be supported by an 800 MHz carrier using conventional 2x2 MIMO.

	800 MHz TDD	3.6 GHz TDD	Source
Power	4W / MHz	2W / MHz	5G NORMA(D2.3)
SE	1.29 bps/Hz (2x2 MU MIMO)	4.19 bps/Hz (64x4, MU MIMO)	5G NORMA (D2.3)
Number of beams / sector	1	4	Nokia. 5G New Radio Technology and performance. June 2017.
Beam gain	17dBi	25dbi	Assumed / input from operator.
ICNIRP reference public exposure level	4 W/m^2	10 W/m^2	ICNIRP guidelines
Relative throughput / unit of exposure	1	10.25	

Table 1: ICNIRP safe emission limits for macro sites

ICNIRP considerations would encourage operators to deploy 3GHz MMIMO as a capacity boosting measure if emission levels are a constraint, rather than sub 1 GHz TDD.

3.4.2 TDD vs FDD

Traditionally mobile communication has used FDD to separate uplink and downlink communication, with two frequency blocks of the same size separated by a suitable separation gap. This arrangement means that other services are often used in the 'duplex gaps' between the uplink and downlink frequency blocks, and is suited to symmetrical communications, such as voice, with the same demand for uplink as downlink.

TDD methods use the same frequency channel but separate uplink and downlink by using the channel at different times. TDD arrangements allow different amounts of time to be used for different directions, and so can support asymmetric services (such as video streaming which is almost exclusively downlink in nature). Another attributes of TDD using the same channel for uplink and downlink is that the base-station can make a good estimate of the conditions experienced by the handset without having to transmit additional measurement data. This is a particular advantage for using multiple antenna techniques which is a key driver for more efficient communications. TDD is the preferred mobile duplex arrangement for frequencies higher than 3GHz where the smaller wavelength allows use of higher numbers of antenna elements to support so-called Massive MIMO. Hence, higher frequencies are being used to deploy MMIMO in wide-band channels, with TDD arrangements allowing approximately 80% of the time for the downlink direction in order to maximise downlink capacity. TDD methods also allow the handset transmitter amplifier to be more efficient, since it doesn't lose energy at the diplexer that separates simultaneous uplink and downlink data transfer as is the case with FDD methods. We note however, that TDD networks need additional care to avoid interference (primarily base-station to base-station). This can be minimised by co-locating sites, synchronising networks and adopting the same percentage of time for the uplink and downlink. Methods of achieving these (other than co-location) are already in place.

TDD could offer a more flexible and efficient approach for mobile communications in sub 1 GHz spectrum, hence the proposal within the Aetha report. In particular, we highlight the issues raised in Annex C of the Aetha report which presented an overview of the 'Use of low-frequencies for TDD':

- In FDD the uplink is underutilised given that downlink traffic predominates in mobile networks
- MIMO requires knowledge of channel state – which can be deduced with TDD (by BS), but needs additional overhead symbols for FDD.
- This overhead becomes large for higher order MIMO. Since only 2x4 or (max) 4x4 MIMO possible in sub-1GHz, FDD MIMO overhead is 'small' for sub-1GHz
- TDD requires time synchronisation and uplink/downlink ratio co-ordination between operators – but supports asymmetric data transfer (as needed to support existing and anticipated future services)
- Constraining adjacent channels to operate with the same channel structure is likely to impose 'small' impact if traffic between operators is broadly similar. Synchronisation difficulties are well understood with working solutions in place.
- TDD works less well for large cell sizes – base station to base station interference can occur with long duration transmit paths – but the impact can be 'small' (~2%). However, it is not clear how this might be implemented and more careful control and management of the network may be needed from an operational perspective
- Issues can arise in cross-border locations in which FDD and TDD operating in the same bands have to coexist in a limited geographical area. However, this is highly unlikely as a defragmentation would need to be done at an EU level

A potential disadvantage of TDD is that the range of the base station can be reduced. In practice the range limitation is due to the power from the handset which constrains received SINR at the base station. TDD handsets currently, and are likely in future, to have the same transmit output power as FDD, but transmit for less of the time. Whilst it would be possible to use additional coding in conjunction with the additional bandwidth availability, a key benefit of LTE (and anticipated future standards) is the commonality of the transmission format used for both FDD and TDD equipment. It would seem unreasonable to allow TDD to utilise more coding options than FDD, and uplink capacity is less likely to be a constraint in range reduced locations (other than indoor coverage). Hence, FDD is likely to have the advantage of supporting improved coverage compared to TDD, even in the yet incomplete 5G standards[21]. This has been incorporated as a potential constraint and noted together with the migration benefits/impact. Thus, full TDD benefits above 3GHz (MMIMO) are not transferrable to sub 1 GHz at present.

3.4.3 Handsets limitations

The Aetha report discusses the economies of scale in devices to support the defragmentation and clearly identifies the need for at least a UK and EU combined market to be adopted in order for any handset manufacturers to be interested. Furthermore, feedback from MNOs indicated that device support is driven by international standards and once this has been established then vendors will take an interest and contribute to development.

Aetha's report also recognised the need for there to be negligible cost increases in device development to support any of the options.

We also agree with the Aetha findings that devices are becoming more agile in supporting additional frequency bands which we know is going to increase with new 5G bands in the mmWave part of the spectrum. However, we acknowledge the possibility that a proportion of customers do (will) not naturally churn to the latest technology even with a protracted replacement period, so there is the potential cost of a scheme to remedy that. In addition, where the installed base has a much longer life cycle such as the latest smart meters and supports the wrong technology, this will also increase the costs of consumer equipment replacement.

There may be uncertainty or unwillingness for vendors to support a new band-plan just for sub 1 GHz spectrum because of the risks in limited market potential, also if this is not taken up globally for example, this could take valuable research funding and resources away from other developments. A study by Real Wireless[22] points out some of the highly sensitive market drivers of the handset vendors with regards to adding new frequency band configurations in future handset models.

Another consideration is the need for operator support for the migration options which in turn drives support for device development. There may be a need for international and flagship carriers to kick start a device ecosystem which again alludes to the need for international support.

A particular recommendation, therefore, would be to understand the appetite for supporting a new sub 1 GHz band configuration from international handset vendors' and operators perspective. In addition, assess the possible global regulatory certainty of adoption as handset vendors may require specific levels of certainty to commit investment to develop a new sub 1 GHz band plan arrangement.

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[21] It is noted that Ofcom's suggested 700MHz coverage obligation in their 700 MHz coverage obligation consultation (https://www.ofcom.org.uk/__data/assets/pdf_file/0022/111937/consultation-700mhz-coverage-obligations.pdf) is based upon the downlink signal level only. In practice, an uplink signal with a similar margin is required to ensure that the necessary 2-way communication path is maintained - service will not be available if either uplink of downlink directions cannot be maintained at minimum quality levels

[22] Terminal capabilities in the 700 MHz band. Real Wireless report to Ofcom. 2013

4 Feasible migration paths

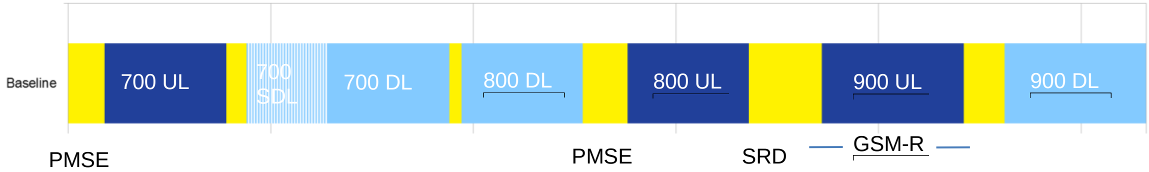
A pre-requisite for any of the options considered in this study is that the migration end-point has established broad support across a wide area within ITU Region 1 (Europe, Africa and the Middle East) and possibly other ITU regions. It is assumed that handsets can be sourced that will support both the starting point and the end point of the preferred band-plan option, and that such handsets will not support any other capability to help facilitate the migration (i.e. we believe that handsets, particularly from major vendors, would not incorporate non-3GPP bands or capability to facilitate re-farming).

It is assumed that any allocations that are removed from the destination band-plan, are assumed to be available for use at the beginning of the migration, and any allocations existent at the beginning and end of the migration are not disturbed during the migration. Spectrum is made available in multiples of 5 MHz to be consistent with anticipated channelisation plans. We anticipate that these migration plans would allow each operator to retain access to some sub-1 GHz spectrum throughout the migration process.

We believe that feasible migration paths exist for all options. There is some flexibility in how migration to different options can be done. It is believed that the migration plans described below are 'reasonable', and though possibly not optimal, are sufficient to identify representative issues and approximate benefits and costs.

4.1 Baseline band-plan

This is the anticipated spectrum use post the 700 MHz spectrum release – consisting of 210 MHz of mobile spectrum. This includes 3 MHz for M2M (733-736 MHz), a new European harmonised band for radio microphones (823-832 MHz), Police and Fire Service (862-863 MHz), and an augmented band for Licence Exempt SRD use (863-876 MHz).



Other gaps without such clear use amount to a further 8 MHz. Presently GSM-R uses 2x4 MHz of spectrum located just below the 900 MHz duplex bands (876-880 MHz paired with 921-925 MHz). Dedicated spectrum for GSM-R is not accommodated in other options.

4.2 Migration to option 1

This is the maximum FDD option. This migration is constrained by needing to migrate multiple duplex bands to another duplex band, with incompatible duplex gap and channel bandwidths. This results in access to a given part of the destination band-plan potentially needing access to (part of) the duplex frequencies of existing bands. This results in a loss of mobile spectrum during the migration.

Option 1 provides 235 MHz of mobile spectrum (with 2 large, contiguous FDD blocks (2x85 MHz), supplemented by two supplementary downlink bands (1x30 and 1x35 MHz)). 5 MHz of gaps and the designated 3 MHz for M2M (733-736 MHz) are reclaimed for mobile use. The European PMSE[23] (wireless microphone band) is retained at 823-832 MHz, together with Home Office use at 862-863 MHz, and 12 MHz of the designated 13 MHz for LE/SRD use[24].

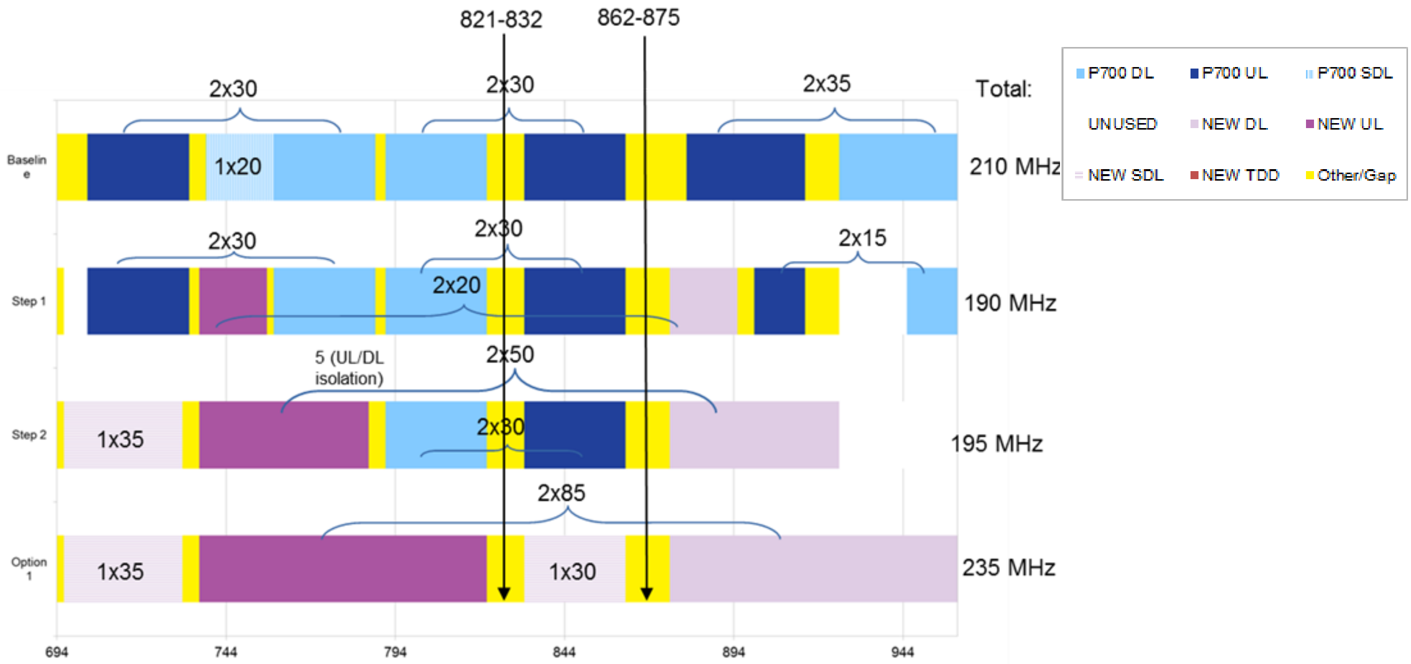


Figure 4: Option 1 step-by-step migration

The main steps are as follows:

- Step 1: Maintain use of 700 and 800 MHz Duplex bands, Re-farm 700 MHz supplementary downlink (losing paired parts in 900 MHz uplink and associated paired spectrum). Retain existing and include new duplex gaps where required. There may be increased interference in the top 2 MHz of the 2x30 MHz band. Assume, may suffer increased interference in top 2 MHz of the 2x30 MHz 700 Band Use 736-756 MHz (downlink), paired with 875-895 MHz (uplink) (gain 2x20) – Lose use of 880-895 paired with 925-940 MHz (2x15) and 700 MHz downlink.
- Step 2: Maintain use of 800 MHz Duplex band – re-farm 700 MHz and reclaim paired spectrum that is available in 900 MHz uplink band. Re-farm the rest of 700 MHz. This provides access to 736-786 MHz (paired with 875-925) (2x50), and the supplementary downlink band 696-731 (1x35 MHz). Access has been lost to the baseline 700 MHz band and 900 MHz bands (2x65, and 1x30).
- Step 3: Refarm 800 MHz band – allowing re-use of unused 900 MHz band and supplementary downlink in 800 MHz uplink band. Re-distribute spectrum use to maximise contiguous blocks. This achieves Option 1 end-point.

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

[24] ERC Recommendation 70-03, Relating to the use of Short Range Devices (SRD), Tromso 1997, updated 30th September 2015.

4.3 Migration to option 2

This option offers most flexibility in timing and migration with little dependence on when existing 3GPP bands are migrated.

Option 2 consists of a total of 235 MHz of mobile spectrum, with 3 TDD blocks (1x120 MHz, 1x30 MHz and 1x85 MHz). Similar to option 1, the harmonised radio microphone band (823-832 MHz), together with Home Office use at 862-863 MHz, and 12 MHz of the designated 13 MHz for LE/SRD use[25].

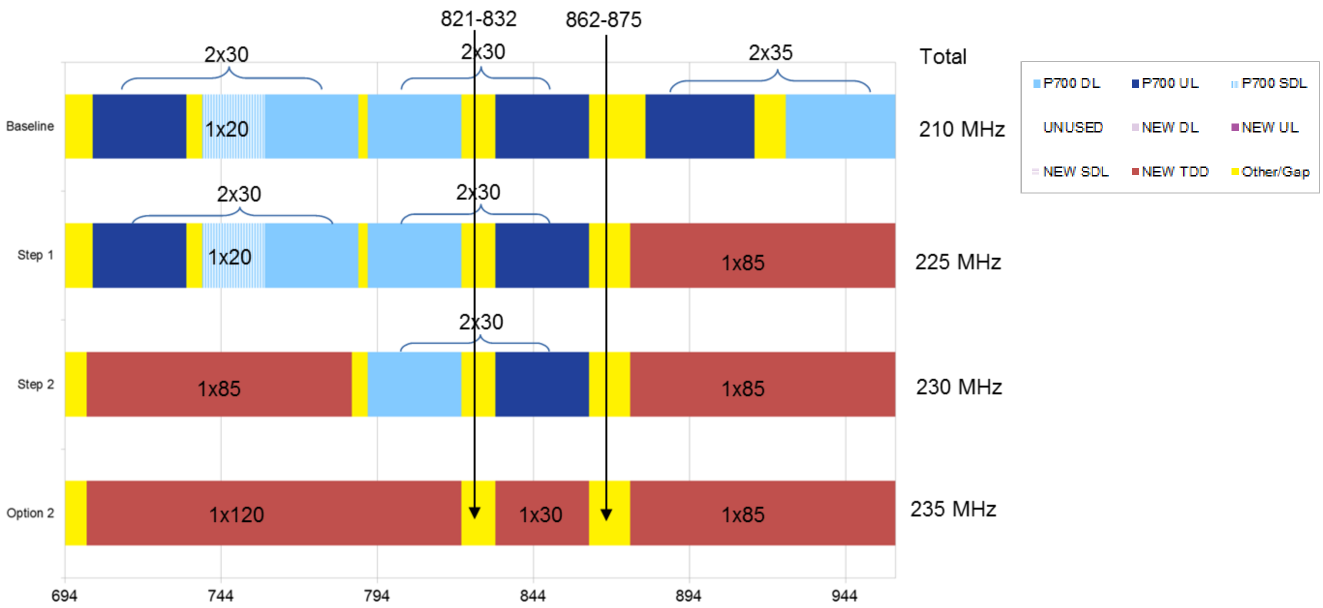


Figure 5: Option 2 step-by-step migration

The main steps are as follows:

- Step 1: maintain use of 700 and 800 MHz bands, including 700 MHz supplementary downlink. Convert 900 MHz band to TDD – reclaiming additional 5 MHz of 862-880 MHz gap. Retain post-700 MHz uses below 875 MHz.
- Step 2: Re-farm 700 MHz band – and realign beginning of TDD at 701 MHz. Increase (2 MHz) gap to protect 800 MHz band from TDD.
- Step 3: Refarm 800 MHz band, allowing re-use of 786-791 MHz and preserving 821-832 MHz. Re-distribute spectrum use to maximise contiguous blocks. This achieves Option 2 end-point.

Migration of different post-700 Award bands could be done in different orders. Re-farming of the 900 initially allows a larger initial spectrum gain. Aetha note that it might be preferable to defer migration of the 900 band to allow time to migrate legacy services and devices (e.g. metering equipment using the 900 MHz GSM band).

[25] ERC Recommendation 70-03, Relating to the use of Short Range Devices (SRD), Tromso 1997, updated 30th September 2015.

4.4 Migration to option 3

Option 3 consists of a contiguous 250 MHz TDD band – achieved by removing access to other users of the band in the range 710 to 960 MHz. Other users of UHF spectrum (such as PMSE and SRD) are intended to be relocated to the 16 MHz gap between 694 and 710 MHz. This option retains much of the migration flexibility as Option 2, but results in loss of access to spectrum during the migration.to facilitate relocation of PMSE and SRD.

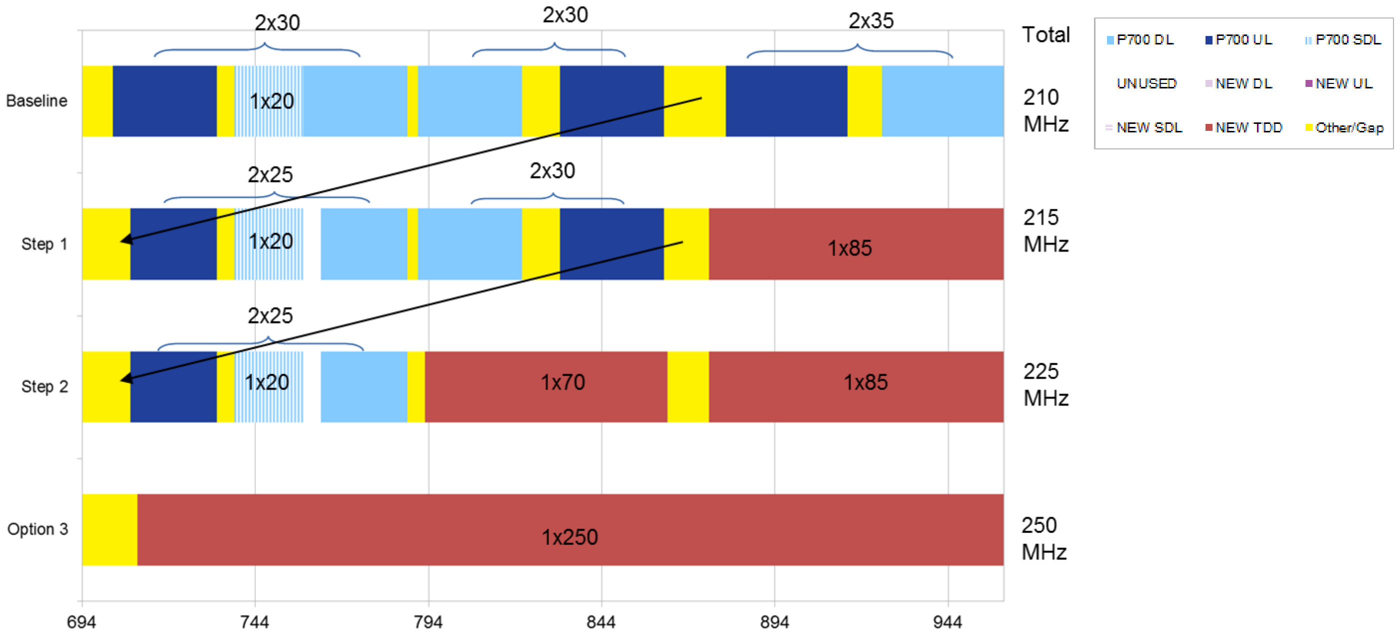


Figure 6: Option 3 step-by-step migration

The main steps are as follows:

- Step 1: Retain (2x25 of) 700 and 800 MHz Duplex bands. Refarm 900 MHz (realigning on PMSE band). Begin migration of other uses to 694-708 MHz.
- Step 2: Retain 800 MHz band – and claim 862-863 MHz from PMSE to allow 70 MHz channel bandwidth, whilst protecting 700 MHz duplex band.
- Step 3: Re-farm all 700 MHz band and reclaim gaps. Re-distribute spectrum use to maximise contiguous blocks.

4.5 Migration option comparison

Figure 7 shows the relative throughputs that can be achieved for each of these migration paths, assuming that TDD is used with an 80/20 (downlink/uplink) ratio, that TDD is 10% more spectrum efficient than FDD.

This clearly demonstrates the achievable long term throughput that is available for each of the options and the losses in Option 1 associated with some spectrum being left unused during the transition. Option 3's gains are not realised till the end of the process owing to the need to leave spectrum unused to facilitate migration of PMSE and SRD.

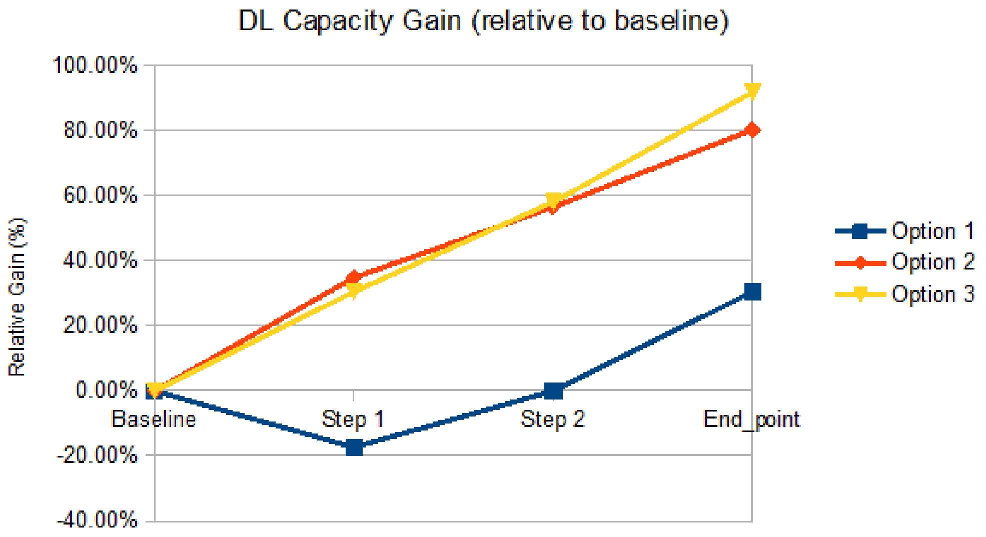


Figure 7: Comparison of three migration options and relative capacity gains

Outcome:

- **Baseline:** There is no change to the band plan configuration below 694 MHz. Capacity gain will arise owing to the aforementioned improvements in technology evolution.
- **Option 1**: Given the need to add as much downlink capacity as possible, this would be the least preferred option of the migration options. It is also complex to migrate and in the first step there is a drop in capacity. It retains the FDD legacy approach which provides certainty for the future for operators with FDD spectrum sub 1 GHz and its coverage/anchor layer but adds cost to change to a new duplex gap arrangement.
- **Option 2**: This would be the preferred option of the three migration options based on retaining most of the existing uses, thus least disruption, with each step capacity increases and offers contiguous bandwidths for multiple operator support. It also offers a significant uplift in capacity compared to today.
- **Option 3**: This would likely be the second most preferred option of the three for mobile operators. This is because it offers the largest quantity of contiguous spectrum. However, it does not retain the existing uses in their allocated bands which means cost and disruption to those users could be significant. In each step, capacity increases and supports contiguous bandwidths for multiple operators.

Given the above outcomes and wider mobile network capabilities we consider the baseline option would deliver sufficient capacity gains where it is needed to help meet the expected mobile data demand in 2030 and beyond. MNOs (will) have a range of methods for targeted capacity increase rather than upgrade their entire network, which is what will be needed for any of the migration options for sub 1 GHz. Thus defragmentation of their sub 1 GHz bands may be an unlikely choice for MNOs to help soak up capacity or deliver additional benefits beyond what other options will be available by 2030.

4.6 Impact to other mobile/non-mobile services

We consider three of the main other users in the UHF band (GSM-R, SRDs and PMSE) that could pose potentially large barriers to defragmentation given their wide geographical spread and dependence on harmonization of frequency bands and interoperability. The other uses including the 1 MHz for ground communications for police and fire and the Met Office bands may pose less of a barrier in comparison.

4.6.1 GSM-R

We consider in more detail the impact the defragmentation has on GSM-R. In the Aetha report it states that although GSM-R has only recently been deployed in the UK, there is already a migration plan to the new Future Railway Mobile Communications System (FRMCS) which will be an LTE-based solution. The current thinking is that FRMCS will use the existing GSM-R and extended GSM-R bands (873-876 MHz/ 915-918 MHz). It is not possible to use the extended band in the UK as the bands are used on a licence-exempt basis. However, the UIC and European Union for railways will consider continuing to use the same downlink and uplink bands to support FRMCS (presumably after 2030) to limit the implementation costs.

There are also interoperability considerations for railways particularly for trains crossing from the UK into France and other countries. This would be another reason for at least EU harmonization for defragmentation. There is scope for the routes to extend beyond those routes already in use across Belgium, France and most recently Holland. We also note, without harmonisation this could have much wider economic implications in terms of transfer of goods as well as business/leisure travellers.

Furthermore, in the rail sector there are long procurement cycles which means decisions on investment need to be taken as soon as possible for future deployments or technology swap out thus a decision for defragmentation would need to be made by 2023 in order for the rail industry to commence planning its implementation ten or so years later.

Major Constraint. The re-allocation of GSM-R within the defragmented UHF band should be given greater consideration and full understanding of the challenges and timescales particularly from a harmonization and interoperability perspective. A change to the allocated GSM-R spectrum is contingent on harmonization throughout Europe.

4.6.2 PMSE

Similar in some way to GSM-R, the decision to allocate the duplex gap in the 800 MHz band (823-832 MHz) to PMSE, provided the sector with some certainty of access and evolves an ecosystem that could co-exist with mobile. Furthermore, the PMSE industry has, in the last ten years or so, continually had to relocate to new bands resulting in additional costs.

Medium constraint. There is a precedent within the PMSE sector to be adaptable and flexible in deployments as has always been the secondary user of the UHF band. The identification of a new frequency range above 960 MHz also presents an opportunity to begin migration over the timescales of this initiative.

4.6.3 Short Range Devices (SRDs)

There is prolific use of short range devices in the UK within the 863-876 MHz band. It is a European harmonised band with tens of millions of devices in operation. Once a band is allocated for use by licence-exempt devices, reversing this decision can be time-consuming and potentially costly. Clearing the band of licence-exempt devices is challenging because:

i) Anyone can buy, use/install and operate devices resulting in potentially an installed base of millions across the country clearing the band of all devices could take many years
ii) IoT operators/vendors such as Sigfox and Telensa use the 868 MHz band and are deploying network infrastructure and selling products in the UK to connect to Smart Meters and other IoT devices. These would need to be moved under option 3. Changing the transceiver for devices such as smart meters is problematic, as they are difficult to access and have long equipment replacement lifecycles.
iii) Any change could create a negative impact on consumers as they will be forced to swap out existing devices
iv) There will be an impact to vendors of devices as they will need to conduct research and testing, develop new chipsets and front ends

However, as identified in the Aetha report consumers with existing products can buy/replace new products through a device refresh but there is no certainty how long it will take to clear all devices. There will likely be a small number of devices that continue to operate long after any transition period, so there is no certainty the band will be totally cleared.

Solutions which are dependent on large investment in infrastructure will suffer from any frequency change. This will require a retune of infrastructure and replacement (upgrade) of end point (e.g. smart meter) devices. The key to resolve the replacement of SRDs will be to start early and identify a target block in the UHF band so that vendors, CEPT studies and other regulatory developments can commence.

Medium constraint. This is could potentially be a major constraint as there is lots of uncertainty and will need European harmonization and agreement of which option to pursue. There is also the need for CEPT studies and research by vendors for chipsets in new bands. However, SRDs tend to be cheap to develop and produce and regulatory and industry could react quickly developing products in the new band once the regulatory decisions have been agreed.

4.7 Costs and benefits

4.7.1 Migration costs

We have identified some key factors that contribute to the costs of migration in the UHF band. These costs are based on the steps that would need to be taken by operators as identified in sections 4.2 to 4.4. The Aetha report indicates the costs to the operators could be low. However, we found from discussions with the mobile operators and other sources that a network upgrade of such magnitude would be complex to engineer and re-design, particularly as the entire macro grid would need to be upgraded and therefore costly and time consuming.

We found the following elements of a network upgrade are the key additional costs to be considered:

- New antennas – to support the full sub 1 GHz and low band, TDD operation and increased number of ports
- RF front ends – development of RF front ends to support the increased channel bandwidth and different duplex gaps
- Feeders, couplers, combiners, testing and commissioning (after each site visit)
- Site visits – to do hardware swap outs, antenna install and commissioning subsequent to 700 MHz deployment
- Equipment swap outs
- Mast re-engineering in cases where the existing mast cannot support the equipment upgrades

A proportion of the costs can be considered business as usual and can be factored in to any future network investment and upgrade by the MNOs. In the case of a frequency migration, we found that 2-3 visits per site would be needed and the need for temporary RF front end equipment to support the step-by-step approach. This would result in write-offs for capex on equipment.

One particular issue raised by MNOs was the temporary loss of spectrum, as found from option 1 (all FDD). This would be commercially damaging to MNOs even as a temporary measure and they would seek compensation for any losses. We were unable to identify a migration for Option 1 consistent with the reasonable constraints identified that doesn't have some temporary spectrum loss.

In the table below we provide an estimate of the likely capex for upgrading existing sites and thus the costs between two operators to upgrade 20,000 sites[26] in the UK.

Estimated capex (£)	Option 1 (FDD)	Option 2 (3 x TDD)	Option 3 (All TDD)
Costs / site (upgrade)	~100,000	~125,000	~125,000
Total costs (million)	2000	2500	2500
Costs/operator (millions)	1000	1250	1250
Cost/year (millions)	200	250	250

Table 2: Estimated costs of network upgrade for each migration option

The estimated capex per operator is approximately £1bn based on two operators sharing majority of the infrastructure. We compare this to other costs to achieve capacity gains from spectrum such as the value of the entire 800 MHz band[27] (2 x 30 MHz) of £1.6bn to achieve lower total quantities of

[26] We assume there will be around 25000 macro sites by 2030 and new ones built for 700 MHz (circa 5000) will not require upgrading

[27] Based on interpolated estimates of value of 800 MHz spectrum in the UK, Analysys Mason, 2013 http://www.analysysmason.com/About-Us/News/Insight/UK-4G-auction-Mar2013/

mobile spectrum (between 17 and 32 MHz from migration options) which appears comparable. However, each operator would need to spend this amount on upgrading their network.

The costs above are indicative and solely represent the capex investment needed to support each of the options (there is no consideration of opex). It can be seen that capex for options 2 and 3 are slightly higher than option 1 but there are greater capacity benefits for those options. The higher costs are a consequence of the increased RF front end cost assumption for these two options. We also estimated an additional £25-100 million for upgrading a small proportion of masts that would need strengthening or re-building to support the new heavier antennas.

4.7.2 Migration benefits

The primary benefits of undertaking the defragmentation process have been identified as:

- Increase capacity in the sub 1 GHz portion 694 – 960 MHz relative to post 700 MHz award (up to 70% increase in downlink capacity) with an increase of 32 MHz spectrum.
- Create a future band-plan to support 5G and new technologies with wider contiguous bandwidths
- More flexible and efficient use of scarce resource, operation cost savings from operating fewer bands
- Early switch off for legacy technologies

The defragmentation options proposed in the Aetha report maximizes the use of the spectrum by moving guard bands, supplementary downlink and existing uses freeing up portions to create wider blocks. We agree each of the options provides the above benefits but as we have identified in this report there will be trade-offs from the practicalities of upgrading the network through to a decision on the step-by-step approach to migrations. There will also be a need to quantify these benefits (and the costs) in more detail particularly the practical steps and time-consuming nature of upgrading each site so that a full cost benefit analysis can determine if the benefits outweigh the costs.

Against these benefits we note that the use of TDD (options 2 and 3) will result in reduced coverage – for the very spectrum whose key benefit is to provide the network coverage layer. If "deep coverage" is not required, operators may prefer to augment the sub-1 GHz connectivity with capacity in higher frequency layers. We note that such capacity can be provided with higher spectrum efficiency and with less additional ICNIRP emission impact in, say, the 3-6GHz band than the sub-1 GHz band. In addition, we note that the gains anticipated from the use of the new band-plans is similar (probably less) than the anticipated SE gains compared to today's technology. However, any benefits of the new band-plans are additional.

5 Relevant legal and regulatory considerations

In this section we discuss any regulatory or legal issues that would prevent a defragmentation from happening in the 694 – 960 MHz band.

We identified two regulatory changes that are necessary to solve in order to achieve defragmentation:

1. Change the use of the frequency ranges that need to change in order to achieve contiguous mobile-use blocks, or reallocation of spectrum and
2. Reorganize the current assignments so that a single user has larger blocks instead of smaller and separate blocks, or reassignment of the frequencies.

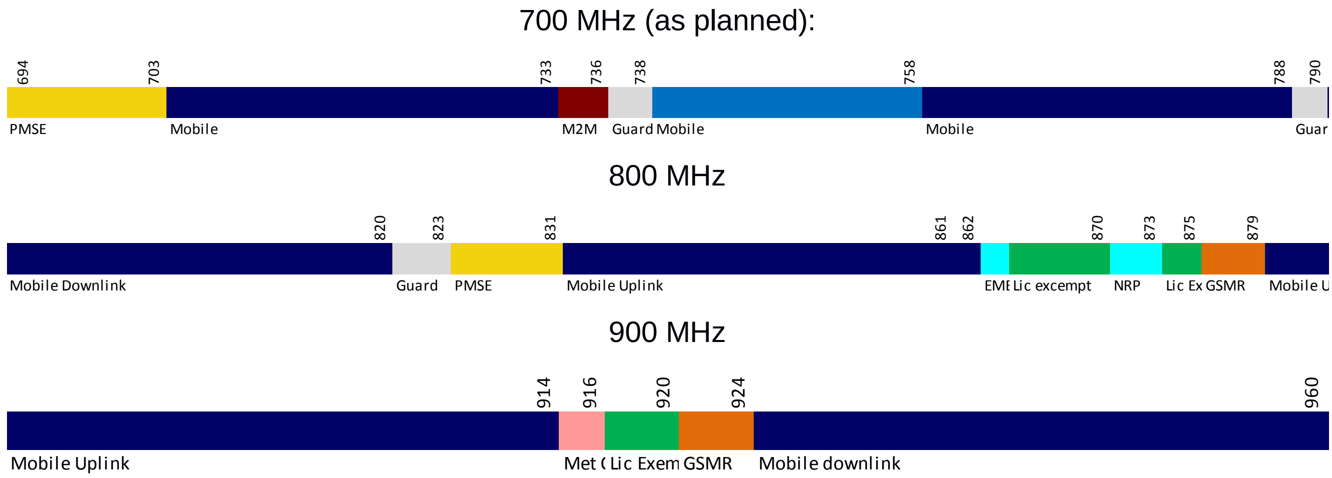
Both of the procedures are not unknown to the UK, as they have been handled before in other contexts such as the repurposing of both the 700 MHz and 800 MHz bands, where the frequencies were reallocated (changed use from mainly broadcasting to mobile) and re-assigned to new users. For the purpose of defragmentation, this will also be the path, but the timings and procedures may differ. Nevertheless, both reallocation and reassignment procedures are possible under the current regulatory framework.

It is important to highlight that in any of the procedures that need to be taken to achieve the reallocation and reassignment, Ofcom is expected to play the leading role to be carried out under their existing obligations and duties, meaning the procedures shall be objectively justified, not unduly discriminatory, proportionate and transparent.

5.1 Reallocation phase

In the first procedure, the reallocation of the spectrum will depend on the degree of defragmentation that is chosen, meaning, which of the 3 proposed scenarios is the one that is going to be achieved. In the current situation, each of the bands houses different services and uses. The 700 MHz will include mobile broadband and supplementary downlink[28], 800 MHz has mobile broadband, PMSE, licence exempt, amongst others and the 900 MHz has mobile, Met Office radar, licence exempt and GSM-R. The current band plans are as shown below:

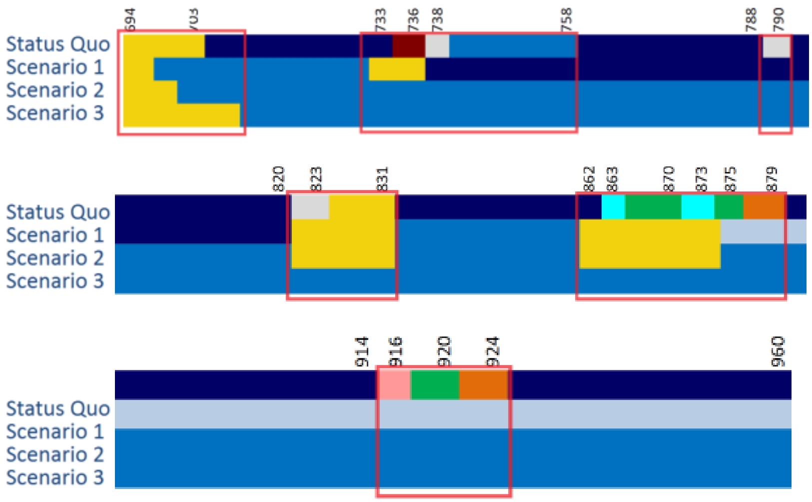
[28] According to the public consultation issued in March 2018 by Ofcom: “Improving mobile coverage: proposals for coverage obligations in the award of the 700 MHz spectrum band.”
https://www.ofcom.org.uk/__data/assets/pdf_file/0022/111937/consultation-700mhz-coverage-obligations.pdf



In the case any of the defragmentation options is chosen, some of the allocations of services will be either slightly shifted or moved to entirely new positions in the band. This means that the users with or without a licence and using the frequencies, will be moved as a result of the defragmentation. This means there will be some clearing of the band of existing users and subsequent reassignment to other services (mainly mobile) and licenced. This procedure will need two instruments:

- A public consultation
- A limitation on the number of licences for the spectrum that has been allocated until now as licence exempt, and will, with the defragmentation, become of "exclusive" or "private" use for just one provider.

The challenge with reallocation of frequencies will be the need to seek Europe wide consensus for the likes of GSM-R, SRDs and PMSE. The process within CEPT, for example is lengthy and in the of GSM-R allocation falls within a European Union mandate to use the current frequency for GSM-R and at present remains the case for the new FRMCS. Thus moving the red squares which are the areas in which there will be significant impact regarding allocation aspects, will need early intervention at European and international level to first understand the potential support from European Member States and more preferably global support.



5.2 Reassignment phase

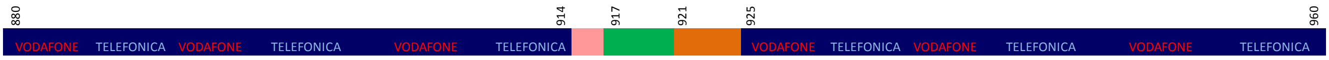
The second step in this process will be to reorganize the assignments in a way in which operators may have larger contiguous blocks. This will involve modifying the granted licences themselves. Modification of licences may happen fairly frequently for spectrum management purposes, but a modification on the actual frequency assignment has rarely happened in the past, while the licence is still in force.

The licence terms may be modified unilaterally by Ofcom when it is deemed necessary under the circumstances listed in Section 3 of the WT Act licence text. Spectrum management is one of those circumstances. From the text of the licences, the specified notice period is only mandatory if the licences are to be revoked, and not if they are being modified. We consider it highly unlikely that any kind of defragmentation can move forward and achieve any positive results without close cooperation between all of the stakeholders involved, operators and regulator. This means, that even without a fixed notice period obligation included in the licences, we are confident that Ofcom will work in partnership with all the affected parties to make sure a suitable notice and transition period is given[29].

The mobile frequency assignments today are shown below. Please note that we do not show the 700 MHz band as the assignments are due to be made after 2020:

800 MHz

900 MHz



As can be seen from the figures above, in both bands the assigned frequencies are interleaved between operators. This situation would change in case any of the defragmentation scenarios were to be adopted. In any case, the operators would have to shuffle their specific frequency ranges to consolidate bigger blocks, which implies that their licence would indispensably have to vary, at least in the UHF frequency range.

What will need to be defined is which operator moves where. As there is no unequivocal mechanism written in the regulations that demonstrate how to decide where each operator shall move, any procedure proposed is most likely to go through a public consultation to be discussed with the stakeholders. It is nevertheless possible to identify some options on the potential ways forward.

1. The specific frequency ranges/sizes are unilaterally decided by Ofcom. Based on the principles of proportionality, transparency and objectivity, Ofcom may decide which operators move where. This can be done founded on technical and economic studies that demonstrate a cost-benefit analysis that reasonably justifies the decision.

[29] The Wireless Telegraphy Act established in Schedule 1, Revocation or variation "6. Ofcom may revoke a wireless telegraphy licence or vary its term, provisions or limitations (a) by notice in writing given to the holder of the licence". This means that even if the established notice period to revoke is not applicable to vary, a due notice period is necessary to modify the licences.

2. The preferred frequency ranges are decided by the operators and stakeholders in multilateral negotiations. All the operators and users can decide to come together to agree on the spectrum
3. The identified frequency ranges are decided by an auction process. Another option is to hold an auction in which the operators bid for the pieces of spectrum they value the most in the bands to be reassigned. It would be a procedure very similar to the ones that have been developed by Ofcom as "Assignment Auctions." Ofcom would have to evaluate the level of competition an auction like this one may have. It is also possible that once the 700 MHz band auction is completed, there is little to no interest in picking one or another range from the other frequencies.
   This Assignment Auction can take place in at least 3 ways (See Annex B):
   - Scenario A: The amount of spectrum an operator has already assigned, plus the amount it is interested in acquiring (that extra MHz that are going to result from the whole defragmentation procedures) in one, two or all bands is aggregated and put into a pool. This is done for all operators. Then, the operators can bid for the assignment of a particular range for the total spectrum they have put into the pool.
   - Scenario B: Once the reallocation process is done, there will be new frequencies available for mobile services. These newly available portions may be auctioned as usual. Operators will bid for MHz (Principal Stage) and then their location on an Assignment Round. After this stage, operators may negotiate between them the amount of spectrum they have bought to be allocated in a specific range, amongst them.
   - Scenario C: The operator can only bid for the ranges that are contiguous to its already assigned frequencies and for the surplus frequencies gained from the defragmentation process.

Clearly, there are many uncertainties and dependencies on how such a process would or could be conducted. This study has highlighted some initial thinking in how a process might unfold given the regulatory framework in place today. It is fair to say the regulatory framework will evolve over time and approaches to regulations will change. This will have an impact on whatever mechanism is needed to undertake a defragmentation such as the one proposed by Aetha.

In conclusion, defragmentation of the sub 1 GHz band is possible under the current regulatory framework. To allow users and operators to access larger consecutive ranges of frequencies, it is necessary to reallocate (change the use in some portions of the bands to and from mobile, depending on the current use and the chosen defragmentation scenario) and reassign (vary the licenses and licence exempt instruments to shuffle the users and operators in a way in which they can access portions of the spectrum that are larger and consecutive). The way forward on how to relocate and reassign will need to go through one or more public consultation procedures to create consensus, led by Ofcom within the principles of transparency, proportionality, no unduly discrimination and objectively justified.

6 Summary of findings

In our study we have taken into account a range of practical and feasible aspects for conducting a frequency migration in the UHF band. Any changes to the network must be viewed in the context of what we anticipate to be standard practice in 2030: Networks will be using multi-band, multi-tenant, multi-service infrastructure, operating in spectrum that is exclusive, shared and some of which will be licence-exempt. The sub 1GHz band will provide a relatively small % of the total network capacity - but a crucial role in supporting the wide-area coverage and anchor layer able to support multi-band operation across all cell types and services.

The objective was to consider the findings from the Aetha report and look in more detail at migration options from a technical/practical and regulatory perspective and respond to some of the suggestions in the report.

In this section we summarise the overall findings from the study.

6.1 Baseline network configuration

We determined what a hypothetical mobile network would be like in 2030 as the capabilities of the mobile network would be vital to understanding any future potential UHF band migration. This was based on developing assumptions from a range of studies but primarily 5G NORMA which provides the novel radio mobile architecture for 5G. The mobile network in 2030 would be advanced in technology terms, however, the sub 1 GHz layer would predominantly be used for a robust coverage layer, providing a minimum service level indoors at most geographical locations across the UK. The main aspect was the physical constraints at UHF and the evolution of the macro layer limited to possibly 4x4 MIMO but most likely 4x2 with significant reliance on carrier aggregation.

Macro sites would support multiple-bands with the low and medium bands providing the high bandwidth capacity and sub 1 GHz wide area coverage.

6.2 Constraints

The constraints identified in this study focus on the practicalities and feasibility of supporting the migration options. The deployment of TDD means there could be a reduction in cell edge performance unless TDD can support additional coding options that are not provided for FDD - which seems unlikely. However, new technology may evolve by 2030 to support this. There will be a need for MNOs to synchronise their networks and cooperate more than they do today. Although TDD networks are not yet widespread and relatively new in the UK we recognise this will increase in future with 5G and that there is no technical barrier and that this will be standard practice for other (TDD) bands. The issue is rather there has not been a great need to coordinate/synchronise between operators to date and this could take time to work through with some uncertainty and hidden challenges which lead to additional overheads and costs.

We found there would be some practical challenges to site upgrades. For example, we considered that in some cases up to three sites visits would be needed to every site in the network to upgrade the antennas and RF front ends as migration takes place. It can be argued that network upgrades will take place anyway and new equipment can be installed but the migration would require additional planning, testing and equipment swap outs leading to greater investment and longer to roll out than might be typical. Furthermore, we found that upgrading of existing sites would bring them closer to the ICNIRP limits but in some small cases, based on our assumptions, the sites would exceed the ICNIRP limits.

6.3 Feasibility of migration

The need for minimum regional buy-in would only occur if the migration and the end-point of the options would offer significant counterbalancing cost and performance benefits. However, despite regional buy-in, it is assumed that handset chipset suppliers will not provide more than the minimum capability needed to satisfy standard 3GPP bands, and the end-point band-plan (i.e. equipment will not accommodate any other duplex/channelisation arrangement than the post 700 MHz and end-point band-plan). Given this, the technical migration roadmaps exist for all options:

- Option 1 (maximum FDD): This migration is constrained by needing to migrate multiple duplex bands to other duplex bands, with incompatible duplex gap and channel bandwidths. This results in access to a given part of the destination band-plan being potentially needing access to (part of) the duplex frequencies of existing bands. This results in a loss of mobile spectrum during the migration.
- Option 2 (TDD retaining many existing users): This option offers most flexibility in timing and migration with little dependence on when existing 3GPP bands are migrated. We have assumed that bands are done on a piecemeal basis so that all operators can always maintain operation in sub-1 GHz spectrum.
- Option 3 (TDD, moving all existing users): This option has many of the benefits of Option 2, but since this option needs to accommodate migration of all existing users results in loss of access to spectrum during the migration. Increased TDD downlink capacity nearly offsets this loss of spectrum.

Any migration to the new band-plans would require standardisation of any preferred band-plan to receive broad support within Region 1 and possibly more broadly. Each of the options can be migrated from the assumed baseline – requiring every macrocell site to be visited on at least one occasion and probably up to three times. Migrating from the baseline to Options 1 and 3 is likely to be more challenging than Option 2.

This would be most favourable for mobile operators in terms of trade-off between cost and benefit (capacity) and limits the need to move all the existing uses (except the downlink part of the GSM-R band is refarmed). However, we would question the need to undertake any form of migration if current technology and network architecture can support the demand growth and utility of sub 1 GHz spectrum.

For example, we acknowledge that LTE-Advanced and 5G NR technology can provide large combinations of carrier aggregation and that the sub 1 GHz band would not be utilized for high capacity provision in all locations. Therefore, possibly in the next 3-5 years and post 700 MHz award, a fragmented sub 1 GHz band provides adequate capacity for operators needs and is largely relied upon for coverage.

However, there is still uncertainty about the quantity of ‘sufficient’ bandwidth needed by operators in sub 1 GHz and how the bands will be used in future. This requires operators to determine and quantify how much more spectrum in sub 1 GHz is needed for capacity given changes in technology and access to higher frequency bands.

We determine the possible technology developments that could occur in the time between now and when defragmentation could take place:

- MNOs decide to re-farm 900 MHz to support future technologies thus increasing the efficiency and flexibility to adopt 5G technology and aligning with the other sub 1 GHz bands
- Further relaxations to planning permissions
- Rethink location and utility of existing guard bands (Ofcom to consider)
- Likely development of improved filtering techniques and handset selectivity could improve as the general increase in the quality of handsets improves

6.4 Legal and regulatory considerations

Defragmentation of the sub 1GHz band would be possible under the current regulatory framework. To allow users and operators to access larger consecutive ranges of frequencies, it is necessary to reallocate (change the use in some portions of the bands to and from mobile, depending on the current use and the chosen defragmentation scenario) and reassign (vary the licenses and licence exempt instruments to shuffle the users and operators in a way in which they can access portions of the spectrum that are larger and consecutive). The way forward on how to relocate and reassign will need to go through one or more public consultation procedures to create consensus. This would be led by Ofcom within the principles of transparency, proportionality, no undue discrimination and objectively justified.

7 Conclusions and recommendations

We conclude that the cost of implementing any of the defragmentation options outweighs the potential benefits highlighted in the Aetha report. This is based on potential network upgrade costs estimating that the capex for upgrading an operators' network from the migration options could be approximately £1bn. This is due to operators typically targeting upgrades to sites and areas in locations where it is needed and the migration would necessitate changes at all sites. Thus, ordinarily and by 2030, we expect a proportion of the total site base would not have a need to increase capacity.

In essence, the cost to an operator to upgrade its whole network (£1bn) for defragmentation is almost comparable to the value of the whole 800 MHz band (2 x 30 MHz – estimated at £1.6bn from the outcome of the 4G spectrum auction[27]) to gain an additional 2% (approximately) capacity relative to total licensed bandwidth per operator. This could be considered a large cost for MNOs by 2030 timeframe as there will be a need for any new band-plan to be applied across the entire network. In addition, there could be other additional costs such as for replacement of handsets for technology laggards (albeit for a small proportion of subscribers) but also the installed base of old technology with long life cycle equipment. Overall, and with these costs in mind, the exercise could be cost-prohibitive from an MNO perspective. There is also the potential cost of migrating the other uses of the UHF band such as GSM-R, PMSE or SRDs but this was not analysed as part of this study.

Much of the claimed benefit of the migration is to facilitate use of TDD at sub 1 GHz. We note:

- Sub 1-GHz, TDD can facilitate a downlink capacity increase of approximately 75% (80% downlink, with 10% spectrum efficiency improvement) compared to FDD.
- The TDD uplink coverage is likely to be reduced. This can limit a key enabling characteristic of the sub-1 GHz layer i.e. to be the coverage/anchor layer for the network.
- Much of the benefits of having access to contiguous spectrum (particularly at sub 1 GHz) are being reduced by increasing capability of spectrum aggregation.
- Increased transmissions from macrocell sites can become problematic. In the absence of updated ICNIRP guidelines for MMIMO, we anticipate that 3GHz (and above) spectrum can support approximately 10 times the throughput for a similar emission increase in the 800 MHz spectrum. This value seems large and would suggest more detailed investigation is required.
- It is also noted that anticipated spectrum efficiency improvements are likely to be higher than the migration gains, though these would be in addition.

Any rational operator would seek to augment their network using the least cost method of providing the capacity and coverage required. Therefore, MNOs would need to clarify under what conditions the anticipated large cost of migrating to any of these new band-plans would be economically more attractive than investing in more spectrally efficient technology and MMIMO capability in spectrum in the 3-6 GHz range. We also suggest that MNOs will have a range of tools available by 2030 to serve capacity increase in targeted areas, rather than a potentially costly wholesale upgrade of the macro layer to support defragmentation of the sub 1 GHz bands i.e. a small proportion of their total spectrum holdings. One key recommendation, based on the outcome of the study, is that a more detailed analysis of the preferred option is undertaken based on least costs as identified in our report, compared against costed scenarios of different mobile network evolutions and potential capacity gains in the current fragmented sub 1 GHz arrangement.

Regarding the impact to other uses (e.g. SRD and GSM-R) and regulatory challenges we identified that:

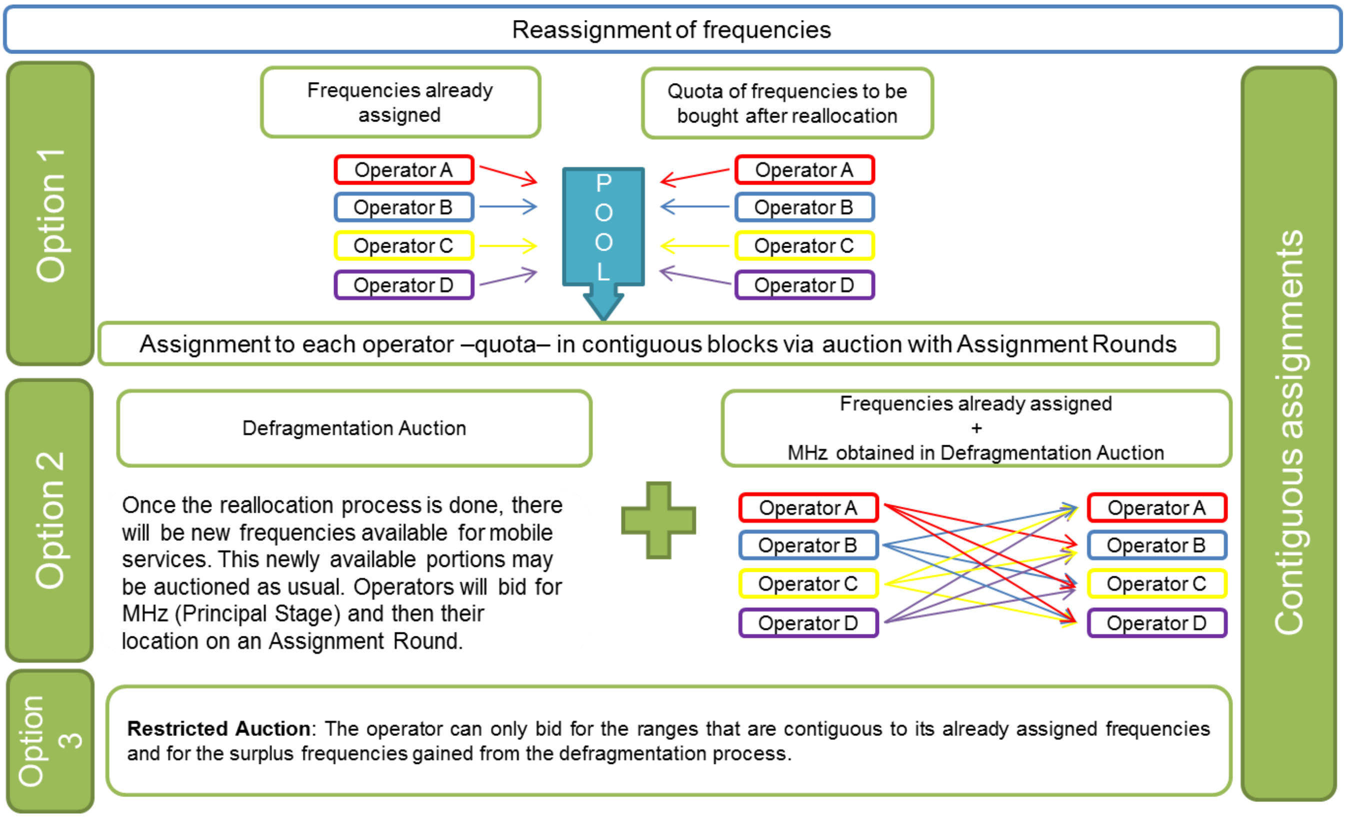
- A prerequisite for any migration is that it would **have to have broad international support** so that a standards based solution can be achieved (broad support of CEPT for example)
- We anticipate there are **no major regulatory hurdles to overcome** in defragmenting the bands below 1 GHz, however it remains uncertain what processes will be used and what legal challenges and risks there would be to and between the operators. For example, there will be challenges in the re-assignment phases and balancing of spectrum holdings across operators
- **Dependencies of interoperability, harmonisation measures and uncertainty of coordinated timescales** are all aspects for further consideration when examining the impact to existing users of the UHF band e.g. PMSE, GSM-R and SRDs
- The numerous regulatory dimensions involved in defragmenting not just the mobile services but PMSE, SRDs and other uses across the entire EU, should not be underestimated. Although, UK will no longer be part of the EU from March 2019, regulatory change can be slow to implement and there remains an imbalance of economies across Europe, some of which may only be planning to introduce new services or devices into the bands now with investment now only starting to come through. This could delay or impose lengthy timeframes for a coordinated and harmonised approach to defragmentation
- Given the costs to undertake any of the migration options, **we expect sub 1 GHz mobile capacity could be achieved at a lower cost** since deployment of new spectrum would only be at sites where it is needed.

We provide some recommendations based on the findings in this study which can support policy makers within government and industry on how to progress the defragmentation proposals, these include:

- Seek the possibility of wide-scale international support of a defragmented UHF band at both ITU-R and CEPT levels and the range of possibilities for further study
- Start a detailed assessment of the step-by-step approach to understand costs, complexity and timescales in more detail
- Study the capacity requirements of mobile services using sub 1 GHz spectrum. Determine when or if there will be a capacity crunch post 700 MHz award (this should include scenarios of each of the options and the baseline)
- Study and quantify in more detail the expected costs to mobile operators, the rail sector, SRD vendors and the PMSE industry to gain a holistic level view of the cost to affected parties
- Refine the baseline configuration of the mobile networks in 2030 with a focus on the likely physical base station setup in terms of new antennas and existing masts capabilities
- Encourage an update to the ICNIRP Guidelines to consider impact of MMIMO antennas and adaptive beamforming above 3GHz.
- Understand the impact of the migration options and upgrade to sites to ongoing Electronic Communications Code revisions. In particular, the relevance to the shared network/shared spectrum/multi-service future and also the consideration or evolution of a national policy to simplify the overheads in site modifications that are likely to arise with the transition to 5G/6G

8 Annex A: Proposed mobile reassignment options

In the figure below, we exemplify the proposed options to achieve the assignment of contiguous blocks to the operators, once the defragmentation has been concluded.



9 Annex B: Relative capacity in the sub 1 GHz band

It is useful to understand the capacity available in the sub 1 GHz band (post 700 MHz release) compared to the total capacity available. We can make the following, reasonably conservative, estimates of bandwidth availability in different bands, spectrum efficiency (relative to that achievable in the sub-1 GHz band, owing to benefits such as MMIMO) and spectrum re-use within a macro coverage area (owing to small cell densification), as shown in Table 3.

	Sub 1GHz DL	Sub 1GHz TDD	1-3 GHz DL	1-3GHz TDD	3-6GHz TDD	MmWave (TDD)
Baseline Bandwidth (assumed) (MHz)	95	20	200	150	150	500
DL ratio	1	0.8	1	0.8	0.8	0.8
Spectrum Efficiency Improvement (relative sub 1GHz)	1	1.1	1	1.1	4.4	4.4
Spectrum re-use factor	1	1	1	1	2	2
normalised DL capacity	1	0.19	2.10	1.39	11.12	37.05
Total normalised capacity	52.8					
% sub 1 GHz	2.2					

Table 3: Capacity of sub 1 GHz spectrum as a proportion of total available mobile bandwidth

In the above table, it is assumed, that:

- 80% TDD capacity is used in the DL, that TDD can achieve 10% higher Spectrum Efficiency than FDD (as used elsewhere in this report)
- With MMIMO, four times the sub-1 GHz spectrum efficiency can be achieved for TDD use above 3GHz
- A small number of small cells supporting spectrum above 3GHz (only 2) will be used in capacity hot spots.

- 500MHz will be made available in the mmWave spectrum.

Flexing these reasonably conservative assumptions, results in the sub-1 GHz supporting around 2% of the total capacity available to be deployed by operators.

Hence, though changes to the sub 1 GHz bandplan result in large percentage improvements (say, 30 - 90%) of the sub-1 GHz capacity, they are only a small capacity improvement given the total capability likely to be available to network operators by the 2030 timeframe.

10 Annex C: Glossary of terms

3GPP	Third Generation Partnership Project
DL	Downlink
DTT	Digital Terrestrial Television
eMBB	Enhanced Mobile Broadband
FDD	Frequency Division Duplex
FRMCS	Future Railway Mobile Communications System
GSM	Global System for Mobile communications
GSM-R	Global System for Mobile communications - Railways
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IOT	Internet of Things
ITU	International Telecommunications Union
LTE	Long Term Evolution (Fourth Generation mobile)
LTE-A	Long Term Evolution - Advanced
M2M	Machine to Machine
Mbps	Megabits per second
METIS	Mobile and wireless communications Enablers for Twenty-twenty (2020) Information Society
MIMO	Multiple Input Multiple Output
mMIMO	massive Multiple Input Multiple Output
mMMC	massive Machine
MNO	Mobile Network Operator
MONARCH	Mobile Network Architecture for diverse services, use cases, and applications in 5G and beyond
NORMA	Novel Radio Multiservice adaptive network Architecture
NR	New Radio (Fifth Generation Mobile)
PMSE	Programme Making and Special Events
PPDR	Public Protection and Disaster Relief
QoS	Quality of Service
SDL	Supplementary Downlink
SPF	Spectrum Policy Forum
SRD	Short Range Devices
TDD	Time Division Duplex

UHF	Ultra High Frequency
UL	Uplink
URLLC	Ultra Reliable Low Latency Communications
V2X	Vehicle to Anything
WRC	World Radio Conference