Opportunities for dynamic or adaptive approaches to managing spectrum in the UK

Annexes

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Annex

A1. Case studies of existing systems

A1.1 This Annex supports our discussion paper on Flexible and Adaptive Spectrum Management approaches. It provides additional details on the three existing dynamic or adaptive spectrum allocation approaches which we identified in our discussion paper as featuring some of the most developed combinations of dynamism and automation:

a) TV White Space (UK)

b) Dynamic Frequency Selection (UK)

c) Citizens Broadband Radio Service (USA)

A1.2 These approaches cover a range of different technical implementations, including more 'device-led' solutions and approaches that rely on database orchestration and tiered access. They all facilitate forms of time-based sharing (interacting with the changing geographic separation from proximate users) to open up new spectrum access opportunities. However, they also all demonstrate how - in different ways - users can over time experience 'knock-on' effects in the form of reductions to or loss of bandwidth, or greater levels of interference.

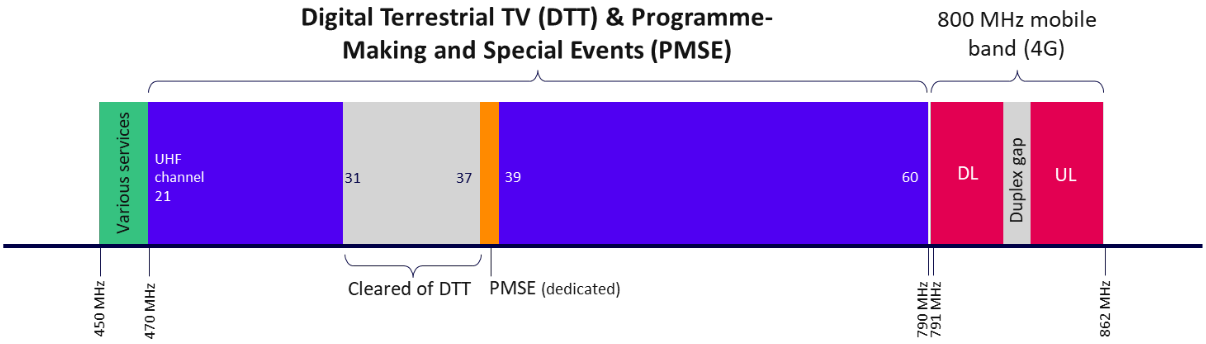
A1.3 By exploring these three approaches in more depth, we seek to highlight some of the practical differences between different device-led and database-led solutions, and how current examples of DSA have evolved in quite bespoke ways to address specific spectrum management challenges. We focus on some of the high-level operating requirements and principles behind these approaches, to identify some of their strengths and limitations, and the factors which made them suitable solutions to the particular problems they address.

Case Study 1: TV White Space, 470-694 MHz (UK)

Context for time-based sharing opportunity

A1.4 'TV white space' refers to usage gaps (or 'white space') across the 470-694 MHz band (part of the UHF band), where the spectrum is currently unused by either Digital Terrestrial Television (DTT), or by Programme Making and Special Events (PMSE) services, which already share the band with DTT on a geographic basis, by sharing channels in different areas.

Figure A1.1: UHF band and adjacent bands at the time of TVWS launch in 2015



Source: Ofcom

A1.5 The growth in wireless communication has led to increased demand for spectrum, and the availability of TVWS offered the potential for more efficient use of spectrum by allowing licence-exempt low-powered devices to access spectrum in the sought-after UHF band.

A1.6 The TVWS framework is a hierarchical model of spectrum sharing in which spectrum not being used by DTT or PMSE can be used opportunistically to offer a range of other services.

A1.7 Initial trials in 2013 and 2014 demonstrated that a number of use cases, including flood sensor networks[1] and remote camera backhaul,[2] could successfully be deployed in TVWS without causing interference to incumbent users. An ETSI harmonised standard was developed for TVWS across Europe and TVWS in the UK was launched fully by Ofcom in 2015.

Technology managing the hierarchy (database-led)

A1.8 TVWS works by allowing whitespace devices (WSDs) to have access to unused spectrum in the UHF band on an opportunistic basis. This access is coordinated through commercially run online whitespace databases (WSDBs), but with devices also playing an important role in ensuring access is appropriately managed.

A1.9 TVWS uses geolocation to coordinate the activity of DTT, PMSE and opportunistic users in the UHF band. It relies on WSDBs making accurate calculations about the availability of spectrum based on data Ofcom provides about the use of the band by DTT services and live PMSE assignments.

A1.10 There are two kinds of WSDs in the TVWS model:

- **Controller WSDs** are able to communicate with and obtain operational parameters directly from a WSDB;
- **Responder WSDs** that can only operate in TVWS under a controller device, which obtains a responder WSD's operational parameters from a WSDB.

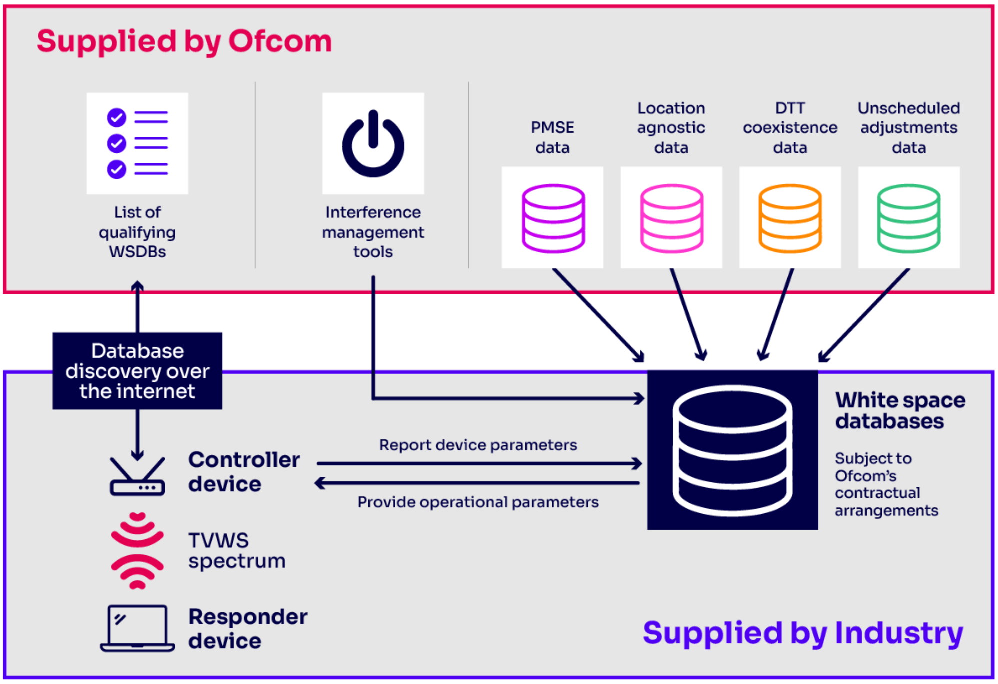
[1] Nominet, 'The Oxford Flood Network', 18 November 2014
[2] BBC, 'Meerkats streamed to YouTube using TV white space', 10 October 2014

A1.11 WSDs regularly provide their location and other technical characteristics (known as 'device parameters') to a WSDB. Based on a WSD's parameters, a WSDB calculates operational parameters, for example the frequencies and maximum power at which a WSD may operate and provides those to the WSD.

A1.12 DTT and PMSE assignments are given priority over WSDs. This means that WSDs are required to respond rapidly and dynamically to instructions from a WSDBs, for example WSDs may have to vacate spectrum in response to a change in need by another spectrum user, or they may be able to increase power levels when another user vacates nearby spectrum.

A1.13 The overall approach is summarised in Figure A2.1 below.

Figure A1.2: Overview of the TVWS framework, including components provided by Ofcom and Industry



Source: Ofcom

Implementation experience for users

A1.14 The configuration of existing DTT and PMSE users (in particular, the concentration of PMSE assignments in urban areas such as London) means that there tends to be greater availability of TV white space in rural areas. The prospect of regularly losing spectrum access may have been a disincentive to users exploring any limited and opportunistic windows for spectrum access in these urban areas.

A1.15 In rural areas, where there was a greater certainty of retaining access for sustained periods of time, interest did develop in TVWS, typically in Fixed Wireless Broadband providing internet access to consumers in rural areas such as Loch Ness[3] and the Isle of Arran.[4] Outside of the UK, TVWS systems based on the model developed by Ofcom were used to provide wireless connectivity in rural areas in several countries (e.g., by Microsoft and Mawingu Networks in rural Kenya).[5]

A1.16 Some of the TVWS rules were considered overly restrictive on WSDs, for example the power restrictions placed on responder WSDs when conducting the initial 'handshake' with a controller device, which limits mobile use cases.[6]

A1.17 WSDB operators have also observed that in some parts of the TVWS model, the data burden is unnecessarily heavy (e.g., the amount of data that must be exchanged and the frequency of these exchanges). This may highlight the importance of implementing systems with the minimum required levels of complexity, as we reference at paragraph 3.31 of our discussion paper.

A1.18 At the time TVWS was implemented, Ofcom was considering making the 700 MHz band (694-790 MHz) available for mobile data use. The consequent reduction in the availability of TVWS spectrum, coupled with restrictions imposed to protect PMSE services in the UHF band's Channel 38 (606-614 MHz) may also have limited the desirability of TVWS for users.

A1.19 Broader adoption and use of TVWS has not materialised. A substantial equipment ecosystem has not developed and all but one of the qualified TVWS database operators have withdrawn from the UK market.

Key Learnings

A1.20 Most candidate WSDs were not accessing this spectrum as a 'top up' user, but as new users with service needs reliant on high QoS levels. The opportunistic nature of access to TVWS spectrum might have acted as a disincentive for those use cases which are more dependent on very high availability.

A1.21 TVWS highlighted that standardisation can provide benefits, especially in creating economies of scale for manufacturers and ease of implementation within different regulatory environments. While the FCC and Ofcom models remain in the US and UK respectively, the Dynamic Spectrum Alliance developed its own Model Rules which enabled TVWS services to be deployed in other markets. These aimed to address restrictions in both the US and UK models and the incompatibilities between them.[7]

A1.22 Effective protection of higher tier services (DTT and PMSE in the case of TVWS) is of paramount importance to build confidence in time-based sharing models. Ofcom's model

[3] Nominet, 'TV white space brings connectivity to local communities around Loch Ness', 21 November 2017
[4] Financial Times, 'Isle of Arran benefits from broadband's white open spaces'
[5] Microsoft, 'Empowering Kenya and the world with high-speed, low-cost Internet', 29 July 2015
[6] The rules state that a WSD must obtain fresh operating parameters when it moves 50 m from its previously reported location. This means a mobile device moving at only 10 mph must obtain new OPs and re-establish its network every 11 seconds.
[7] We recognise there may be benefits from such a standardised approach – however, our current position is that for the UK, with an existing framework and relatively limited set of users, these benefits may not be justified by the costs of imposing further changes.

demonstrated that WSDBs can assume responsibility for protecting those services and that coexistence calculations made by WSDBs play a critical role. WSDB operators demonstrated the ability to perform those calculations accurately and reliably. TVWS also demonstrated that the technology is present for devices to be manufactured which are frequency agile and can be coordinated by online databases.

A1.23 In summary, the UK's TVWS system faced commercial and practical challenges, in particular the lack of an existing equipment ecosystem. However, it was a successful proof of concept and highlighted the possibilities for automated, database-assisted spectrum sharing between multiple users based on both temporal and physical separation.

Case Study 2: Dynamic Frequency Selection, 5.8 GHz (UK)

Context for time-based sharing opportunity

A1.24 In recent years, demand for fast, reliable Wi-Fi has grown hugely in the UK, driven by the growing needs of newer applications such as gaming and video streaming.

A1.25 In response to this growth in demand, Ofcom decided to allocate additional spectrum in the 5 GHz band for Wi-Fi and other related wireless technologies. The 5.8 GHz (5725-5850 MHz) band was opened for Wi-Fi in 2017 and it has increased the number of available wide-bandwidth channels for Wi-Fi, enabling faster speeds and lower latencies.

A1.26 The 5.8 GHz band was already allocated for military and meteorological radar in the UK, and so there was a risk that Wi-Fi use in the band could create harmful interference.

A1.27 To facilitate coexistence between Wi-Fi and radars, Ofcom required that Wi-Fi and other users in the band use Dynamic Frequency Selection (DFS). This requirement applied both to licence-exempt indoor Wi-Fi use and licensed outdoor Wi-Fi use.

A1.28 DFS is a standardised[8] sharing solution designed to prevent interference to radar systems and facilitate greater spectrum efficiency.

A1.29 DFS was initially required for both indoor and outdoor use in the 5.8 GHz band, but this requirement was lifted for indoor Wi-Fi in 2020.

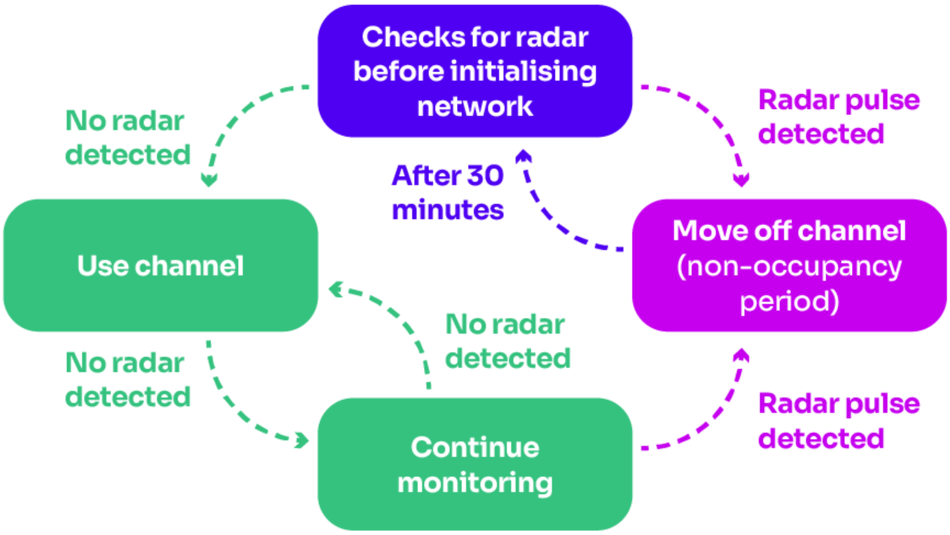
Technology managing the hierarchy (device-led)

A1.30 DFS is an automated system which facilitates spectrum sharing between radar and other wireless technologies, based on measurements undertaken by the equipment seeking to transmit in the band. In the 5.8 GHz band, DFS-enabled Wi-Fi devices scan the band for radar-free channels to operate on, switching channels when they detect radar activity to avoid harmful interference.

A1.31 An overview of the DFS system is provided in Figure A1.3 below.

[8] IEEE Standard 802.11h-2003, Part 11

Figure A1.3: Overview of the DFS system



Source: Ofcom

A1.32 This sensing is undertaken by the master device within a network (for example, a Wi-Fi router), which will scan and swap channels where needed. The client device (for example, a handset) will then respond to pick up operations in the available channel.

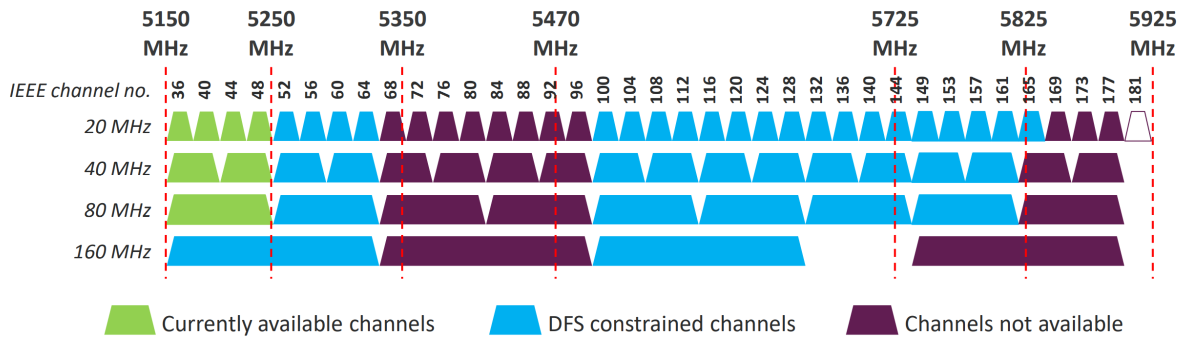
A1.33 DFS is also required in countries other than the United Kingdom and is a standardised system across Europe. In different countries, radar systems use different channels in the band. DFS therefore uses geolocation to ensure that in a given country Wi-Fi devices avoid the channels radar are operating in.

Implementation experience for users

A1.34 Using DFS can affect Wi-Fi performance, as the DFS system forces Wi-Fi devices to switch channels when they sense co-channel radar use. In effect, this presents as a **reduction in available bandwidth** for a system operating across the 5 GHz range. While this reflected the intended operation of DFS, some users also experienced what they considered to be ‘false triggers’ where the presence of an incumbent was sensed, and a channel scan initiated, when this was not always required.

A1.35 As a result, many Wi-Fi users and operators chose only to use channels that are not subject to DFS requirements. This limited the potential for 5.8 GHz to address possible congestion in other parts of the 5 GHz Wi-Fi band without DFS, especially as the maximum channel sizes in those parts of the band are narrower, as shown in Figure A1.4 below.

Figure A1.4: Example Wi-Fi channel plan in the 5 GHz band, prior to the removal of DFS



Source: Ofcom

A1.36 The DFS requirement was enabled using a combination of software and hardware, which made equipment cheaper to manufacture and built on the existing ecosystem of Wi-Fi devices. Nevertheless, some Wi-Fi users and operators chose to avoid the restrictions by falsely geolocating themselves, so that they could access channels subject to DFS without listening for radar.

A1.37 The DFS requirement was removed for indoor Wi-Fi use by Ofcom in 2020 as newer evidence had suggested that the risk of interference from indoor users to radar systems was minimal. This decision brought the UK into line with other major markets such as the USA and meant more traffic could be spread across the 5.8 GHz band.

A1.38 The DFS requirement does remain in place for outdoor Wi-Fi use, as the higher power levels of outdoor operations and lack of building entry loss means that there is a greater risk of harmful interference to military and meteorological radar.

Key Learnings

A1.39 DFS demonstrated that low-power Wi-Fi devices could be frequency agile to protect specific incumbents, and that existing incumbents (in this case radar) could be protected from harmful interference via automated processes embedded at the device level, without recourse to a database.

A1.40 The technology development underpinning this demonstrated that it is possible to maintain an ecosystem of equipment supporting real-time device-led sharing of spectrum, especially where standardised solutions are developed across markets.

A1.41 DFS also highlighted that dynamic spectrum sharing is feasible without specialist or prohibitively expensive equipment in cases where industry has agreed on an acceptable standard. This is more likely to happen when the reward for doing so (in the case of DFS, economies of scale across the Europe-wide market) is sufficient. This opportunity may have been more commercially attractive to support given it was enabling additional access as a **'top up'** to existing spectrum supply.

A1.42 However, the experience of DFS highlights some of the remaining challenges with more independent, device led systems, especially where sensing is heavily relied upon (including the risks of differing implementations even within a standardised framework). It also demonstrated some of the downside’s users can experience when access to bandwidth is incrementally reduced or removed, including potential interruptions to service and impacts on quality of experience.

A1.43 The removal of DFS for indoor devices shows that the right approach to sharing in a given band for a given set of devices may need to change over time. This could be either in response to the changing nature of devices or consumer demand, or simply in the face of updated data and assumptions from users.

A1.44 In summary, while DFS was challenging for indoor Wi-Fi attempting to operate in the same band as other users, it demonstrated a number of important lessons which are still relevant when considering adaptive spectrum allocation today. In particular, it demonstrated that when a standardised solution is developed across markets manufacturers can be incentivised to develop frequency-agile technology. It also highlighted the potential role of information gathered at the device level to support dynamic coexistence between different users.

Case Study 3: Citizens Broadband Radio Service, 3.5 GHz (USA)

Context for time-based sharing opportunity

A1.45 Rising consumer needs and the emergence of new use cases with data intensive requirements is driving increased demand for mobile broadband. The 3.5 GHz band (3550-3700 MHz) is ideal spectrum to provide 5G coverage that can meet these needs, as it offers a good balance of coverage and capacity, and is harmonised for mobile use.

A1.46 In the USA the band was already used by the Department of Defence for naval shipborne radar systems, as well as by civilian satellite earth stations. These uses only operated at certain times, and in certain geographies (which sometimes change over time) but were considered difficult to move to other bands. The FCC therefore took the decision to enable dynamic, time-based sharing in 3.5 GHz, and to allow existing and new commercial users to operate alongside military radar and other incumbent users.

A1.47 The Citizens Broadband Radio Service (CBRS) system was developed to facilitate this, with a view that having shared access in the band would encourage innovation.

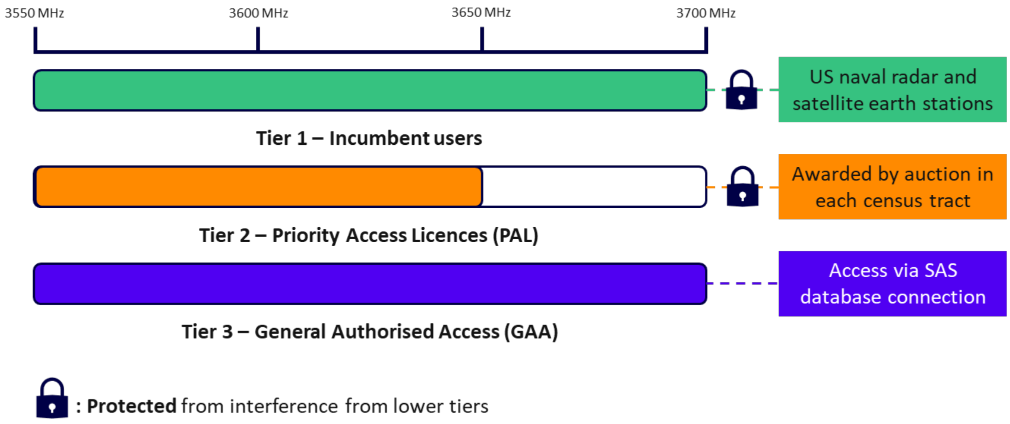
A1.48 CBRS trials started in 2017 and following their success, CBRS was commercially launched in 2020. A set of common technical standards for deployment was developed by the Wireless Innovation Forum industry group.

Technology managing the hierarchy

A1.49 The CBRS system works by dividing the users of the 3.5 GHz band into three tiers, as shown below and illustrated in Figure A1.5:

1. **Incumbent Access – tier 1**: In the 3.5 GHz band this is naval radar and some civilian satellite earth stations. These users are protected against interference from tier 2 and tier 3 users.
2. **Priority Access Licences (PAL) – tier 2**: These licences are auctioned by the FCC. Each one gives the licence holder access to a 10 MHz channel in a single US census tract.[9] Each census tract has seven available PAL licences, and a single licensee can have up to four of these. PAL users are protected against interference from tier 3 users. Many PAL users already hold other spectrum access rights, and are accessing this spectrum on a **'top-up'** basis.
3. **General Authorised Access (GAA) – tier 3**: These are unlicensed and opportunistic users. They have no guarantee of protection from interference from higher tiers and may potentially experience incremental reductions in the quality of spectrum access from other GAA deployments (although database providers can seek to manage this risk).

Figure A1.5: Overview of CBRS tiered framework



Source: Ofcom; adapted from Celona

A1.50 Incumbent users are protected by a network of sensors. These are set up on the coastline and provide an Environmental Sensing Capability (ESC) which detects activity from the naval radars. Once the ESC has detected radar activity it informs the Spectrum Access Systems (SAS), which it is required to do within 60 seconds. It should be noted that this current sensing capability targets a specific incumbent use, and would not necessarily be able to detect a different set of incumbent users if the approach was exported to other bands.

A1.51 The SASs are commercial databases which manage the CBRS system by coordinating the activity of the different users in the band to avoid interference.

[9] Census tracts are relatively small and enduring statistical subdivisions of a county, primarily used by the US Census Bureau and others to provide a stable set of geographic units for the presentation of statistical data.

A1.52 Where different SASs admins are responsible for neighbouring areas SAS admins are required to exchange data as requested, which they are required to do in under ten seconds.

A1.53 SAS admins also maintain databases of all operating devices in the CBRS system (CBSDs) which are classed into two different types:

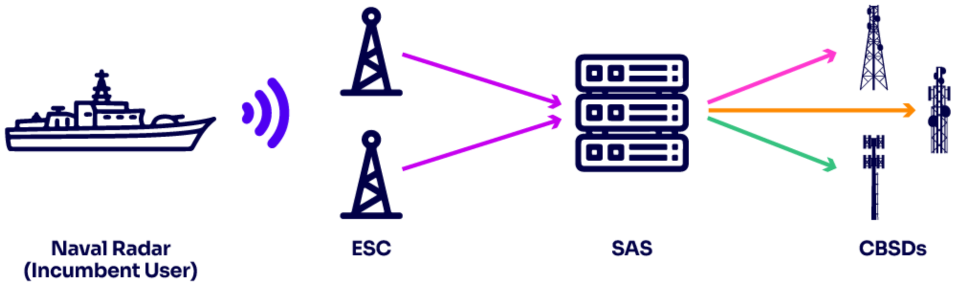
- **Class A**: for indoor, low power use; and
- **Class B**: for outdoor use.

A1.54 For a registered CBSD to begin operating, it must send a spectrum inquiry request to its SAS. The SAS replies with detailed information about frequency availability and any other relevant information that will help the CBSD determine which frequency range to operate on. If the spectrum inquiry request is incomplete, the SAS rejects the request.

A1.55 If an ESC communicates to the SASs that it has detected radar activity, SASs can then require CBSDs to cease transmission, move to another frequency range or change power level and CBSDs are required to do this within 60 seconds.

A1.56 The CBSD in turn will require the End User Device (EUD) to discontinue operations, change frequency, or change power level and EUDs are required to do this within ten seconds.

Figure A1.6: Overview of the CBRS sensing network



Source: Ofcom; adapted from Deepwave Digital

A1.57 To support this system and ensure the smooth operation of this approach, equipment which operates in the band must meet certain requirements, and be approved as being compatible with the band ecosystem. These requirements (which may introduce additional costs to deployments) include capabilities for two-way communication with the SAS databases, power control, frequency agility and a set of security standards.[10]

Implementation experience for users

A1.58 There are now six companies operating as SAS admins and two companies operating as ESC admins. These databases manage access for the PAL users, and coordinate GAA use. The databases are supported by the ESC system which protects incumbent users from interference.

[10] See page 48 of the WinnForum standard WINNF-TS-0112 for relevant user equipment requirements.

A1.59 The prioritisation of the three tiers in CBRS has enabled existing users to continue to access the spectrum they need, while allowing other users to be authorised alongside them. Take-up has been significant, and since the CBRS system went live in 2020, over 270,000 CBRS devices have been deployed.[11] The local level of the auctioned PAL licences encouraged bids from existing and new spectrum users, and over 20,000 PAL licences were auctioned, raising $4.6 billion.[12]

A1.60 For many, this access is a 'top-up' to alternative forms of spectrum access and provided an early opportunity to deploy 5G technologies.[13] There remain, however, potential knock-on effects for these users.

A1.61 In the case of PALs, these knock-on effects come from the prospect of temporarily losing access where a higher tier user is detected. We note that while the ESC system has been effective in protecting existing users, some reports indicate there have been some challenges associated with this. This includes the impact of 'whisper zones' around the sensors,[14] where user equipment cannot be installed to protect sensor sensitivity, and challenges with false positives reducing certainty of access in the band.[15] We note that work is also underway to explore an 'Incumbent Informing Capability' as an alternative to the present ESC approach.[16]

A1.62 For GAA users, this impact can be either in the form of a loss of access, or **incremental reductions in quality** of access as the band fills up. This is because there is no requirement for prioritisation within the GAA tier and in certain areas this has led to reports of increasing congestion and interference between devices.[17] While this can be regarded as a demonstration of demand for this access, it also highlights some of the challenges of managing incremental reductions in the quality of spectrum access resulting from dynamic sharing. We note that while a number of proposals have been developed to support SAS administrators voluntarily improving coexistence outcomes (such as that prepared by the OnGo Alliance[18]), the FCC's technical advisory group has recently highlighted a continuing need for greater certainty to be provided for GAA users.[19]

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[11] FCC Technological Advisory Council, Advanced Spectrum Sharing Working Group, 'Recommendations to the Federal Communications Commission Based on Lessons Learned from CBRS', December 2022

[12] Celona, 'CBRS Auction: Who Won and How You Can Still Get Access', 16 August 2021; WInnForum, 'Inside the CBRS Ecosystem', December 2022

[13] It should be noted that to support sharing, this opportunity is typically at lower powers than would be authorised for block assigned deployments. See Rysavy Research, '5G Mid-Band Spectrum Deployment', 11 February 2021, p. 11

[14] An illustration of CBRS whisper zones can be found in Annex D of the WinnForum report WINNF-RC-1016, 'Coexistence between the 3.45 GHz Service and Environmental Sensing Capability Sensors in the 3.5 GHz Citizens Broadband Radio Service'.

[15] Federated Wireless, 'Environmental Sensing Capability vs Incumbent-Informing Capability', 9 December 2020

[16] National Telecommunications and Information Administration (NTIA), 'Incumbent Informing Capability (IIC) For Time-Based Spectrum Sharing'.

[17] Ericsson, 'Is CBRS for everybody? – growing pains and progress towards a practical solution', 7 September 2022

[18] OnGo Alliance, 'CBRS Coexistence Technical Specifications: CBRSA-TS-2001, V3.1.0', 17 July 2020

[19] FCC Technological Advisory Council, Advanced Spectrum Sharing Working Group, 'Recommendations to the Federal Communications Commission Based on Lessons Learned from CBRS', December 2022, p. 7.

Key Learnings

A1.63 The FCC decision to offer 5G spectrum initially through shared access in the 3.5 GHz band showed that operators and manufacturers can be incentivised to invest in dynamic access systems and that in the right circumstances such systems can be commercially viable.

A1.64 The ecosystem of CBRS devices has grown significantly, reflecting the fact that the CBRS system offers a large market to manufacturers which, in conjunction with the spectrum on offer sitting in the middle of a valuable spectrum band harmonised for 5G, has driven a technological ecosystem. It has also highlighted the capability of commercial entities developing algorithms and database-led systems to ensure coexistence. However, as highlighted above, a number of components of this ecosystem (e.g., sensors and CBSD base station equipment) are currently specific to this band, and successfully developing this ecosystem elsewhere could require an equivalent market scale and set of incentives to manage some of the costs and trade-offs involved.

A1.65 CBRS has provided additional spectrum access and established an access route for innovative use cases, notably private networks for enterprise. The OnGo Alliance has developed as an industry group of almost 200 members focused on establishing private networks in the 3.5 GHz band.

A1.66 However, some critics of CBRS have argued that in many areas of the USA spectrum use in the 3.5 GHz band is low,[20] and that the majority of PAL licences are being used for mobile spectrum access (which brings benefits, but some observers consider may not match the innovative use cases originally envisaged).[21] It is notable that many of the PAL users hold access to spectrum in other bands, and that this spectrum provides a 'top up' to their access, particularly for licensees in coastal areas where the risk of losing spectrum access to a higher tier user is greatest.

[20] CTIA, 'CBRS Spectrum Occupancy Measurements', 28 January 2022
[21] Recon Analytics, 'CBRS: An unproven spectrum sharing framework', November 2022

A2. Further detail on relevant technical developments

A2.1 This annex supports our discussion paper on Flexible and Adaptive Spectrum Allocation. It provides additional details on some of the challenges (and remaining opportunities) we highlight there for more advanced dynamic sharing. In particular, we focus on:

a) challenges with more independent device-led dynamic sharing, including **Cognitive Radio** (which we highlighted in paragraphs 3.12 and 3.46) and associated developments;

b) challenges associated with more '**collaborative sharing'** (which we identified as the most nascent of the four sharing categories outlined at paragraph 2.8);

c) opportunities flowing from the further exploitation of usage **data to support inter-service sharing** (which we highlight as an ongoing challenge at paragraph 3.30).

Technical challenges for more advanced dynamic sharing

A2.2 As set out in our main document, we have identified four main approaches to spectrum sharing: **geographic separation**, **time-based** sharing, **underlay** and **collaborative** sharing. We explained that most forms of DSA rely on time-based sharing of some kind, which can also interact with geographic separation (e.g. 'time-based' gaps may occur in one place when a user moves somewhere else).[22]

A2.3 Today, this is often orchestrated and managed by an intelligent database in communication with user devices, which can control the time periods at which those devices access the band.

A2.4 Device-led approaches such as 'listen-before-talk' Wi-Fi protocols have also been implemented, though these stop short of fully fledged Cognitive Radios able to make their own independent decisions over which frequencies of spectrum they access, and when.

The promise and limits of Cognitive Radios

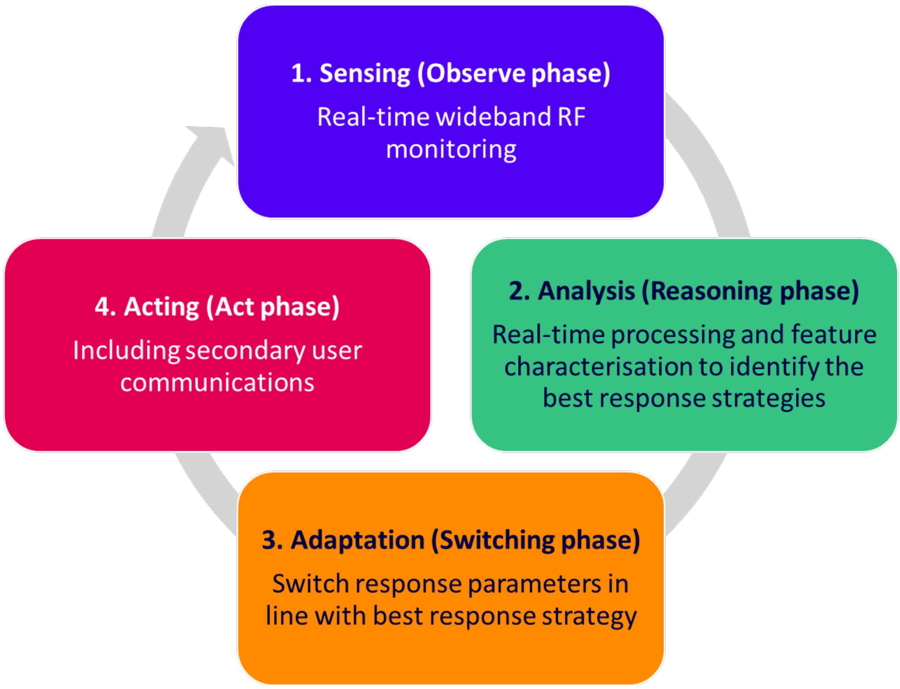
A2.5 The ultimate goal of much research in the area of dynamic spectrum access has been the development of Cognitive Radio (CR) solutions, where individual devices are sufficiently aware of the radio environment, and sufficiently intelligent, to agilely seize momentary gaps in other users' access.

A2.6 According to this vision, a CR will automatically detect available channels, and change its transmission or reception parameters based on other activity within its radio environment, to allow more concurrent wireless communications in a spectrum band at one location. The basic mechanisms supporting this vision of CR is illustrated in Figure A2.1. However,

[22] We set out the fundamental mechanics of this in paragraphs 3.7-3.9 of our discussion paper.

such a solution remains largely theoretical today (and there are always likely to be limits on device-led access to information about passive receive only devices, as we discuss below).

Figure A2.1: Cognitive Radio cycle



Source: Ofcom; adapted from Technische Universität Chemnitz, "Cognitive Radio"

A2.7 One of the key challenges for CR is limitations in spectrum sensing capabilities, especially at a device level.

A2.8 Spectrum sensing is a technique which monitors a specific frequency band to identify used and unused channels by detecting the presence of current users. This can either be provided by (i) integrated sensors in receiving equipment or (ii) independent sensor devices.

A2.9 The advantage of integrating spectrum sensing capability into equipment is that it does not require a separate sensing network, potentially reducing latency and the complexity of any central coordination. However, integrating spectrum sensing capability into equipment will introduce costs (e.g. by increasing the computation complexity required at the device, and the power consumption if more sophisticated detection techniques are used).[23] Some of these trade-offs might be mitigated by optimising the sensing rhythm to only search for other users on a more occasional basis, but the effectiveness of this mitigation will depend on the nature of other users in the band, and how regularly they might be likely to appear.

A2.10 Some studies have proposed using independent sensor devices to offload the sensing activities of receiving equipment and improve sensing latency (by allowing more continuous sensing, rather than wrapping this around transmission patterns).[24] To facilitate

[23] Youness Arjoune and Naimaa Kaabouch, "A Comprehensive Survey on Spectrum Sensing in Cognitive Radio Networks: Recent Advances, New Challenges, and Future Research Directions", 2 January 2019
[24] Deepak G. C. and Keivan Navaie, "A Low-Latency Zone-Based Cooperative Spectrum Sensing".

finding an available channel and the smooth switching from one channel to another, efficient coordination between the sensing network and users will be required. Moreover, as spectrum use moves increasingly towards higher frequency bands, the shorter propagation ranges associated with this may require denser deployment of sensors to fully capture gaps in user activity.

Passive receivers and the hidden node problem

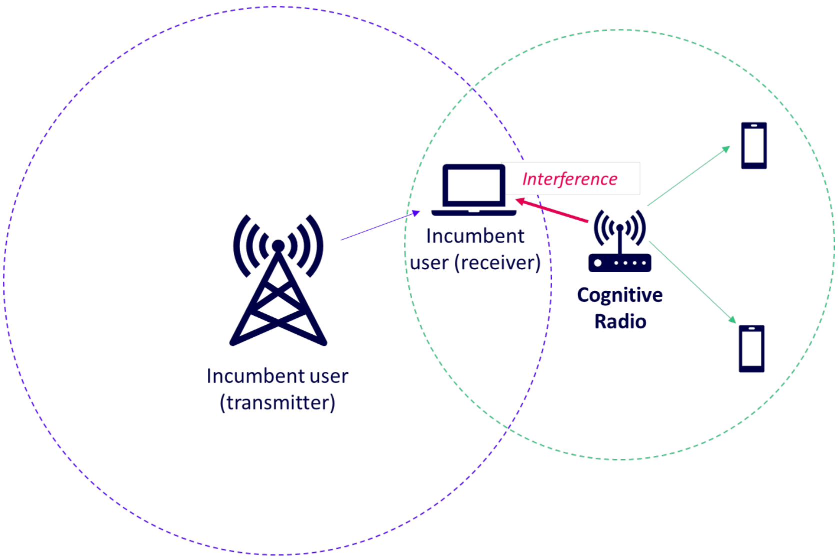
A2.11 Beyond the potential cost and complexity of both sensing approaches, the detection of users can remain a challenge.

A2.12 The potential presence of passive receivers means that even fully fledged Cognitive approaches will always need to be allied with, or supplemented by, some additional data capturing these spectrum users, since the presence of these passive services cannot be 'sensed'.

A2.13 This issue can also extend to 'hidden nodes' where the signal-to-noise ratio of a transmitting device is low, or a neighbouring transmitter is hidden (either because of geographic shielding of its own signals, or because it is in receive only mode at the point that sensing occurs).

A2.14 Figure A2.2 illustrates this 'hidden node' problem.

Figure A2.2: Hidden node problem

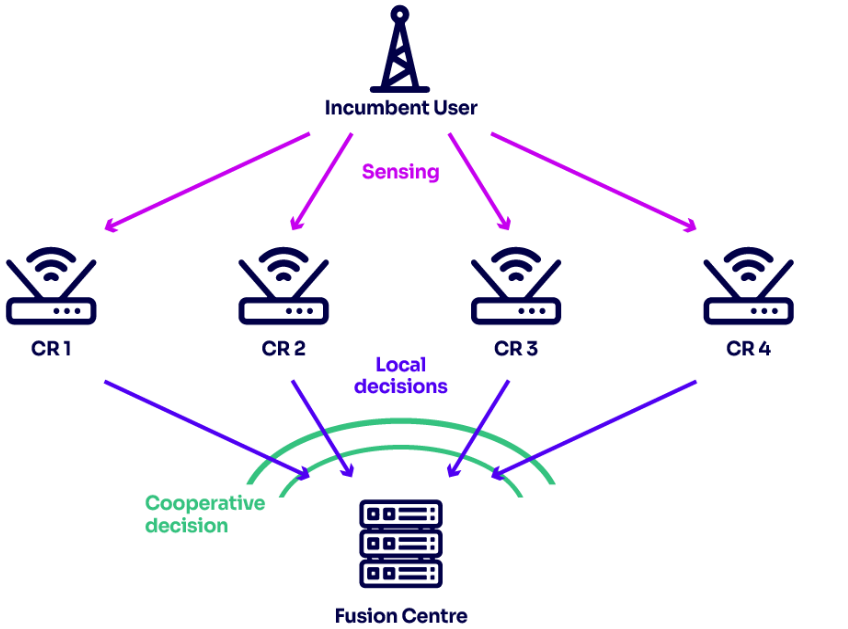


In this figure, the dashed lines represent the operating ranges of an incumbent user and the sharing CR device. In the figure, the incumbent's transmitter is outside the operating range of the CR. As a result, the CR may falsely determine the frequency band is vacant and cause interference to the incumbent's receiver.

Source: Ofcom; adapted from Yücek and Arslan, A Survey of Spectrum Sensing Algorithms for Cognitive Radio Applications

A2.15 To address the hidden node problem, cooperative spectrum sensing has been proposed as a solution, effectively pooling the environmental knowledge of all devices in an area to make the best decisions on usage. Figure A2.3 shows a cooperative spectrum sensing model where each CR reports its individual observation to a central processer, known as a Fusion Centre (FC), capable of analysing this data and making usage decisions across all systems in the band. This decision will be broadcasted to all users. The transmissions between the CRs and FC, and the decision-making process by the FC, both add latency to the overall system. Recent research is investigating different approaches to enhance the sensing performance by using machine learning techniques to support this cooperative spectrum sensing.[25]

Figure A2.3: A centralised cooperative spectrum sensing model



In this figure, observations on the radio environment are gathered by all operating systems in an area, thereby covering a wider range of different radio paths. These can then be shared with and analysed by a 'Fusion Centre' to determine which channels are available for different devices.

Source: Ofcom; adapted from Aykildiz, Lo and Balakrishnan, "Cooperative Spectrum Sensing in Cognitive Radio Networks: A Survey"

Summary of challenges associated with sensing and Cognitive Radio

A2.16 While there are a range of developments that can be considered to refine sensing capabilities, these all come with trade-offs in terms of costs, computational complexity and latency. Though we have seen independent sensing mechanisms deployed (such as the ESC in CBRS, as outlined in paragraph A1.50 above), and sensing instituted at the device level (such as in DFS, as described in Annex A1) these are more limited implementations focussed on detecting specific systems in specific locations. There is currently no commercially scaled solution for a comprehensive sensing and decision-making function at the device level, and even were this to be developed, it is likely supplementary data would be required to protect passive systems.

[25] Zhang Yirun, "Machine Learning-Based Full Duplex Communications and Cognitive Radio Networks", July 2022.

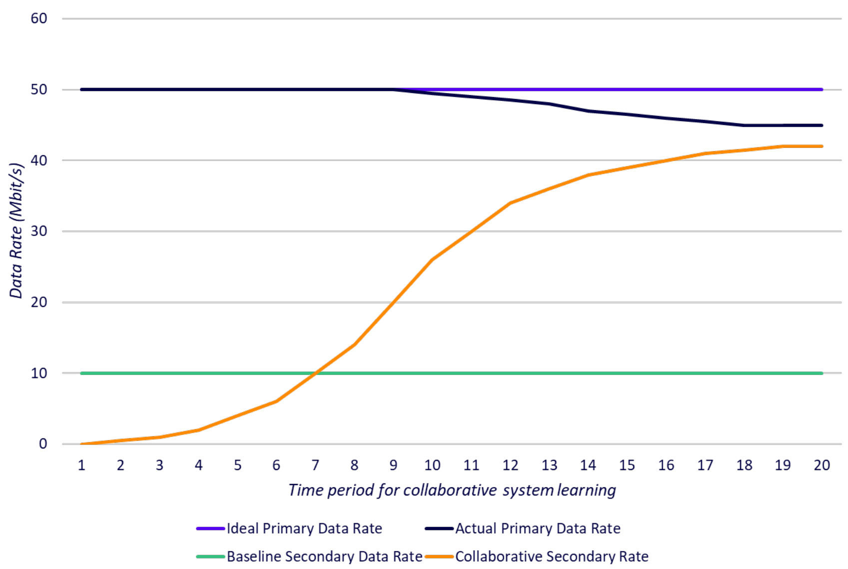
Collaborative sharing holds promise but has practical and commercial barriers to development

A2.17 We noted in our discussion paper that research is also continuing to explore alternative, more **collaborative** scenarios for device-led sharing of radio resources, as highlighted in paragraph 3.37.[26] [27]

A2.18 Essentially, such a collaborative approach relies on the idea that through the exchange of coding and transmission schemes, and the application of learned behaviours, systems can over time achieve a high level of spectrum access on a near-simultaneous basis, and need make only quite small changes or sacrifices to enhance overall performance.

A2.19 For example, all systems might need to accept a slightly lower operating power level and throughput potential to allow other systems to operate nearby, but with a significant increase in the collective throughput. An illustration of this effect across two sharing systems is shown in Figure A2.4 below:

Figure A2.4: Illustration of potential effect of collaborative sharing



This figure illustrates a hypothetical peak data rate a single system is expected to achieve, alongside the baseline level a secondary user might expect if seeking access in a non-coordinated fashion, and what can be achieved over time with collaboration.

Source: Ofcom

A2.20 Over time, and with the adoption of suitable standards, there may be opportunities here to leverage very detailed knowledge of precise transmission powers, time slots and transmit and receive antenna configurations to support much tighter sharing or coexistence than is possible today. Indeed, coordinated multi-point transmissions are already embedded in 5G Unlicensed standards to support simultaneous transmissions within a network,

[26] Liang Dong, Yuchen Qian & Yuan Xing, "Dynamic spectrum access and sharing through actor-critic deep reinforcement learning", *EURASIP Journal on Wireless Communications and Networking*, 4 June 2022.
[27] We note that the sharing of such information across networks may, in future, require further regulatory scrutiny with regards to any commercially sensitive data exchanges, and may also present security issues requiring further consideration.

demonstrating the potential to achieve gains through coordination (if only here on an intra-network basis).[28]

A2.21 However, while collaborative approaches hold promise, they rely on the exchange of detailed network information and clearly defined shared objectives. There may also be practical barriers to its adoption, since it seeks to prioritise overall outcomes (e.g. total throughput achieved) beyond sustained QoS for individual systems or customers. Consequently, we see little sign of commercialisation of these approaches, and where they may take off, it currently seems most likely to be within common networks.

Advanced Data Exchange and Analysis may develop to support more inter-service sharing

A2.22 While fully fledged Collaborative Sharing across networks is challenging to achieve in part because of the levels of real-time data sharing required, advances in the ability to capture, exchange and analyse significant volumes of data may still be key to unlocking more dynamic sharing opportunities. This will be particularly powerful where such data and processes are standardised in a way that is commonly understood across networks.

Artificial Intelligence and Machine Learning

A2.23 Already, there is significant interest within networks in the potential for artificial intelligence and machine learning to improve network and performance planning. These features can help reduce latency, and in the future may help network equipment respond more quickly to a request from a central database to change its transmission frequency or power level, or even pre-empt where such a request is likely.

A2.24 As capabilities advance, such AI developments could support the ability of databases to more rapidly analyse gaps in spectrum usage at a more granular level of time, and across greater bandwidths, to identify more sharing opportunities, and come up with alternative spectrum access options to provide greater certainty of access for users. Such tools might hold the potential to support the kind of ‘multi-band guarantee’ we describe in paragraph 3.41. The increasing adoption of Artificial Intelligence within individual networks today may also be important to build confidence in - and compatibility with - such a regime in the future.

Data exchange and deep analysis to support specific cross service sharing scenarios

A2.25 In our discussion paper, we noted some of the challenges in achieving sharing across different services, particularly at a device level, where some degree of standardisation is typically required. We consequently highlighted some of the potential benefits of more common and open interfaces that might allow a number of services to interact with a common spectrum access database.

[28] Qualcomm, “How does unlicensed spectrum with NR-U transform what 5G can do for you?”, June 2020.

A2.26 Nevertheless, we note that there are other opportunities for advancement, and that there remains potential to develop specific solutions based on data exchange and deep analysis of specified pairs of services.

A2.27 One example is the work ongoing to capitalise on opportunities for sharing dynamically between satellite and mobile services.[29] This is a complex challenge for a number of reasons, including the high directionality of satellite antenna (which can open the prospect for spatial sharing but also means there is a need to assess a wide range of interference paths) and the sensitivity of receivers (which typically have much lower noise floors than terrestrial systems). Nevertheless, interest is emerging in opportunities where this could be managed based on dynamic differences in areas of operation, and taking advantage of the potential to achieve increasingly narrow service beams.

A2.28 The recent 'ASCENT' programme, supported by Airbus, VTT and Fair Spectrum (a dynamic database provider) explored scenarios where database-controlled License Shared Access (LSA) could enable this co-existence.[30] Research is also proposing the development of Integrated Satellite Terrestrial Communication Networks (ISTCN) where user information is encoded into the transmission and shared across systems, similar to the 'collaborative sharing' described above, which would allow receivers to decode the wanted signal only.[31]

A2.29 These scenarios are considered particularly promising as part of a wider 'network of networks' solution where future connectivity for a single device or user is provided by a range of platforms including terrestrial, airborne and space. Similar studies have also explored the potential to share more dynamically between other pairs of services, including mobile and Wi-Fi.[32]

A2.30 Such studies highlight the potential opportunities and gains that can be envisaged from targeted technical solutions in specific inter service sharing scenarios, but remain largely at a research stage. This is indicative both of the potential that may be gained from developing more tailored sharing solutions across pairs of services, but also the challenge of moving niche solutions beyond the research stage, and the opportunity that a more common set of open interfaces might support in the future.

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[29] For example, the Dynasat project.
[30] ASCENT Project, "ASCENT strategic recommendations: Spectrum sharing between satellite and terrestrial systems", 5 October 2020.
[31] Xin Liu, Kwok-Yan Lam, Feng Li, Jun Zhao and Li Wang, "Spectrum Sharing for 6G Integrated Satellite-Terrestrial Communication Networks Based on NOMA and Cognitive Radio", 27 January 2021.
[32] For example, Q. Chen, X. Xu and H. Jiang, "Spatial Multiplexing Based NR-U and WiFi Coexistence in Unlicensed Spectrum", and G. Naik and J. Park, "Coexistence of Wi-Fi 6E and 5G NR-U: Can We Do Better in the 6 GHz Bands".