Deliverable D1.9 Insights report: Conclusions and Next steps

Spectrum sandbox project Work Package 1 deliverable

A report from Real Wireless, Digital Catapult and Qualcomm supported by Freshwave

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Acronyms

Abbreviation	Meaning
AP	Access Point
BLER	Block Error Rate
BS	Base Station
CEPT	European Conference of Postal and Telecommunications Administrations
CoL	City of London
CQI	Channel Quality Indicator
CSI	Channel State Information
CW	Continuous Wave
DL	Down Link
DSIT	Department for Science, Innovation and Technology
ECC	European Communication Office
EIRP	Equivalent Isotropic Radiated Power
eMBB	Enhanced Mobile Broadband
ETSI	European Telecommunications Standards Institute
FAQ	Frequently Asked Questions
IoT	Internet of Things
IIM	Interference Impact Metric
IMT	International Mobile Telecommunications
ITU-R	International Telecommunication Union-Radiocommunication
mMTC	Massive Machine Type Communications
PMN	Private Mobile Networks
PRB	Physical Resource Block
PSD	Power Spectral Density
PDSCH	Physical Data Shared Channel
RSSI	Received Signal Strength Indicator

RLAN	Radio Local Area Networks
RMS	Root Mean Square
SINR	Signal to Interference and Noise Ratio
STA	Stations
SAL	Shared Access Licence
TCP	Transmission Control Protocol
TCO	Total Cost of Ownership
UDP	User Datagram Protocol
UE	User Equipment
UL	Up Link
URLLC	Ultra-Reliable Low-Latency Communications
WAS	Wireless Access Service
WP	Work Package

1. Introduction

DIST has commissioned a Real Wireless-led consortium, consisting of Digital Catapult, Freshwave and Qualcomm to develop spectrum-sharing solutions under the spectrum sandbox project. The project consists of three work packages:

- Work package 1 (WP1) – Field trials in a sandbox environment to assess the feasibility of intensive spectrum sharing between different technology pairs.
- Work package 2 (WP2) – Simulation and modelling to assess the applicability of the sharing solutions to a wider range of technical parameters, locations, frequencies and technologies.
- Work package 3 (WP3)—Economic and regulatory assessment aiming to assess the economic value of sharing solutions and suggest options for exploring potential regulatory mechanisms and tools.

Overall, this work will inform Ofcom and DSIT's policy thinking and help shape new regulatory approaches related to how spectrum is authorised in the UK.

During this study we conducted field trials using the following technology pairs:

1. Wi-Fi and mobile in the upper 6 GHz band (U6, 6425-7125 MHz)
2. Independently operated private networks in the upper n77 band (3.8-4.2 GHz)

The implementation of 'spectrum sandboxes' aims to explore the potential for enhanced spectrum sharing between various service types. The primary objective is to gather data to inform the government and Ofcom, emphasising the role and feasibility of more intensive spectrum sharing alongside an appropriate authorisation model. As articulated in the Spectrum Statement from April 2023, the focus is on promoting innovation and investment while ensuring positive consumer outcomes. The project assesses the impact from the consumer perspective in collaboration with Ofcom to maximise the benefits derived from innovative spectrum applications and services. Additionally, it considers opportunities for spectrum-focused innovation support to leverage the value generated through spectrum sandboxes.

1.1 Organisation of the document

Section 2 presents the analysis of Wi-Fi and mobile sharing in the upper 6 GHz band (U6, 6425-7125 MHz).

Section 3 presents the results of our analysis on independently operated private networks in the upper n77 band (3.8-4.2 GHz). Firstly, we present insights from the interference prediction model improvements for the shared access licence (SAL) framework in the UK. We then present the outcome of the interference tolerance measurements and potential amendments to the SAL licensing process.

Section 4 discusses the future directions, particularly about automation and Artificial Intelligence (AI) for spectrum management.

Finally, section 5 presents the recommendations for further work.

2. Technology pair 1 – Wi-Fi and mobile in the upper 6 GHz band

2.1 The status quo and problem statement

The study aims to evaluate the effectiveness of the reception of the cross-technology signalling as an enabler for intense spectrum sharing between mobile and Wi-Fi services. The study's outcome will determine how strong the correlation between the successful reception of cross-technology signalling and the observed service degradation for one or both technologies is.

In May 2024, Ofcom published its vision for the Upper 6 GHz band, expressing a desire to see sharing between mobile and Wi-Fi services to maximise user benefits. Ofcom has collaborated with international partners to advocate for harmonised standards. On February 13 2025, Ofcom issued a consultation [1] proposing to authorise the band's use by both types of services through sharing. The proposal consists of a phased approach that includes introducing low-power, indoor Wi-Fi into the band as soon as feasible, and a timeline to incorporate mobile services into the band later once European harmonisation is more advanced. Ofcom also mentioned that it is looking for sharing mechanisms to facilitate coexistence between the two services. In this spectrum sandbox project, we investigated the viability of a co-channel coexistence mechanism that leverages cross-technology signalling between Mobile and Wi-Fi as a trigger for Wi-Fi to vacate the channel and therefore avoid uncontrollable degradation of the Mobile service.

In the meantime, European Conference of Postal and Telecommunications Administrations (CEPT) has started working on a harmonised approach that also considers shared use of Upper 6 GHz by mobile and Wi-Fi. It has studied a range of Wi-Fi and mobile network deployment scenarios, including studies of medium power mobile base stations intended to provide adequate outdoor coverage and higher-power mobile base stations providing coverage indoor as well. Studies that consider co-channel deployments and utilisation of cross-technology signalling, assumed that Wi-Fi would yield to mobile use of the channel at the point when Wi-Fi detects a mobile signal or is informed of mobile operations via some other means. The draft European Communication Office (ECC) Report does not recommend a preferred solution, as it is outside the scope of the current report. The draft ECC report also explores an indoor-outdoor division between Wi-Fi and Mobile service, respectively, and an option for band segmentation. The publication of this report is scheduled for July 2025. In December 2024, the Radio Spectrum Committee mandated the CEPT to explore the coexistence of existing services in the band with potential new Wi-Fi and mobile technologies. The mandate aims to investigate the possibility of sharing the spectrum between these services and to propose harmonised technical conditions that will facilitate both Wi-Fi and mobile uses. In addition to various interim milestones, the mandate requires that final reports be published by July 2027.

2.2 Proposed solution

2.2.1 Introduction to the sharing solution

We studied spectrum sharing between mobile and Wi-Fi, an application of Wireless Access Service (WAS) including Radio Local Area Networks (RLAN), operating in the upper 6 GHz band with both networks utilising an overlapping channel. This combination of services is being proposed in the UK [2] and being explored in some other countries internationally, although the exact mechanism for how these two services might share these spectrum resources is still under debate.

Sharing between Wi-Fi and mobile services in the upper 6 GHz band is a relatively new concept that Ofcom held an initial consultation on in July 2023 [3]. In the sharing model, illustrated in Figure 1, the mobile service base station is deployed outdoor and operated under the licence conditions required by the licensed spectrum. Wi-Fi would conform to the license-exempt conditions, with the Wi-Fi Access Point (AP) installed in indoor areas service Wi-Fi stations (STA).

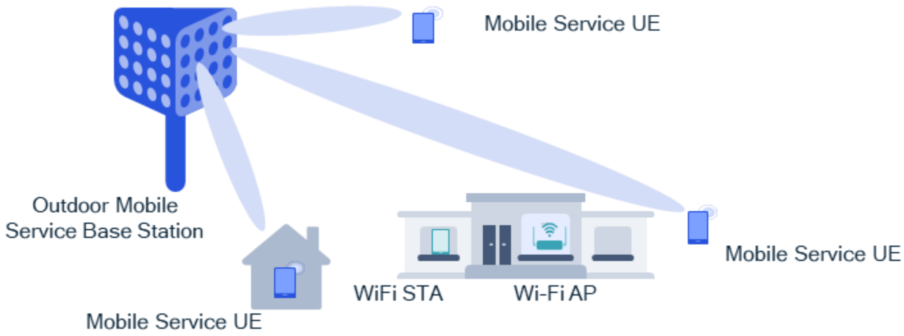

Figure 1: Spectrum sharing model, with outdoor mobile service base station and indoor Wi-Fi AP.

The requirements for mobile and Wi-Fi in the upper 6 GHz are conflicting. Indoor Wi-Fi deployments would benefit from the reduced EIRP limits imposed on mobile service base stations. However, a lower EIRP limit could significantly reduce the coverage area of the base station. When base stations cannot utilise full standard power, it would be difficult to maintain the connections with devices at the cell edge and deep indoors mobile devices. From the mobile network's cost perspective, the reuse of existing sites optimised for 3.5 GHz deployments is necessary.

Regardless of the deployed base station power, a solution is needed to prevent degradation of service for both technologies when Mobile service and Wi-Fi are deployed over the same geographical area. When concurrent use of spectrum is not feasible, the spectrum sharing solution should lead to service reduction but not service degradation. During the project, we explored the feasibility of sharing the band and the extent of service reduction to operate successfully.

2.2.2 Practical measurements via Spectrum Sandbox

The field trial results indicate that when Wi-Fi and Mobile deployments are collocated, spectrum sharing between 5G and Wi-Fi may lead to a significant degradation for both technologies. Our field trial tested utilisation of cross-technology signalling as a tool to identify scenarios that may lead to service degradation and trigger interference mitigation techniques.

The field trial considered utilisation of Wi-Fi waveform for cross-technology signalling, as it is more economical to modify mobile transmitters than Wi-Fi receivers. The utilisation of IEEE 802.11bc framework to transmit cross-technology signalling data ensures that all Wi-Fi 6E hardware is suitable for use. This will help to leverage economies of scale, as IEEE 802.11bc feature can be enabled through software without hardware changes. Generation of IEEE 802.11bc waveform may also be implemented in software on the 5G side. Figure 2 illustrates the use of cross-technology signalling. The IEEE 802.11bc framework allows the content of the cross-technology signalling messages to be forwarded to the destination address/server. The content of the cross-technology signalling is considered Higher Layer Payload (HLP), so the length of the message and content is flexible and can be customised for this use case.

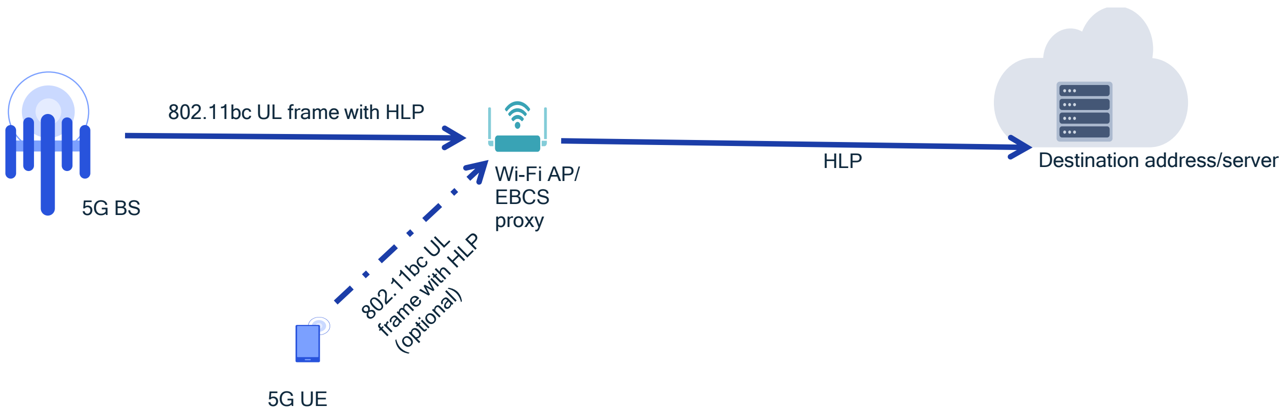

Figure 2: Utilising IEEE 802.11bc for cross-technology signalling.

The field trial test cases could be grouped into 3 different scenarios.

1. Scenario 1: Considers the placement of Wi-Fi AP and STA at the edge of the cross-technology signalling message coverage (from 5G BS and 5G UE).
2. Scenario 2: Considers the Wi-Fi AP placed at the edge of the cross-technology signalling coverage, while Wi-Fi STA is within the cross-technology signalling range (path loss between 5G UE and Wi-Fi STA is 10 dB less than for the first scenario).
3. Scenario 3: Considers both the Wi-Fi AP and STA being placed close to 5G UE and within cross technology signalling range.

The field trial results demonstrate that the transmission of cross-technology signalling by 5G Base station (BS) and User Equipment (UE) and reception by Wi-Fi AP and STA could be an effective technique to identify potential service degradation scenarios and trigger interference management procedure, (e.g. Wi-Fi equipment selects a different channel), provided practical considerations discussed below are fully addressed.

For the first scenario, where the signal strength of the cross-technology signalling is close to the Wi-Fi receiver sensitivity, the loss for both technologies were either not measurable or relatively low (up to 9%).

For the second scenario, significant losses were observed for both technologies, with losses approaching 73% for International Mobile Telecommunications (IMT) and 45% for Wi-Fi.

In case of the third scenario, for some test cases we observed stalling of IMT traffic due to strong Wi-Fi interference while for the others we observed stalling of Wi-Fi traffic due to strong IMT interference. Our conclusion is that for scenario 3, quality of service for both technologies is unpredictable.

It should be noted that the effectiveness of cross-technology signalling depends on its range, the receiver sensitivity and maximum EIRP of the technology that receives cross-technology signalling. The configuration that is considered in our demo was max EIRP=23 dBm for 5G UE, maximum Equivalent Isotropic Radiated Power (EIRP) = 45 dBm (with the antenna gain of 18 dBi) for 5G BS, max EIRP=19 dBm for Wi-Fi AP and STA with cross-technology signing message bandwidth of 20 MHz and Wi-Fi traffic transmitted over 80 MHz. It should be noted that the cross technology signalling range can be improved through higher transmit power, while impact of Wi-Fi to 5G can be reduced by increasing Wi-Fi transmission bandwidth, effectively reducing power spectral density (PSD) of the transmission and thus reducing interference to 5G.

The field trial results indicate that the above mentioned set up provided sufficient range for the cross-technology signalling for a typical Wi-Fi receiver sensitivity and that interference mitigating action was required as soon as Wi-Fi was able to detect the message.

2.2.3 Simulation and modelling results via Montecarlo analysis

The study of the performance impact of spectrum sharing between mobile and Wi-Fi deployments operating in the same band was extended with the use of statistical simulation tools based on Montecarlo analysis, to assess the sharing conditions over a range of parameters greater than was possible in the field trial. No IMT deployments in the other bands are considered in our simulations.

The simulations showed that when no sharing technique is implemented, if the IMT UE and Wi-Fi AP are active in the same location, the baseline reduction of the IMT Down Link (DL) throughput is on average 27%, while IMT Up Link (UL) throughput is on average reduced by 34%.

If the UE and AP are active in randomly and uncorrelated locations, little to no impact to IMT DL throughput is noticed, while IMT UL throughput is reduced on average by 10%. Percentile reductions are computed with respect to baseline IMT values simulated without any Wi-Fi interference.

On the other hand, when cross technology signalling is active, active Wi-Fi APs are reduced to 0-14% of the overall deployed Wi-Fi AP population, and the impact to IMT is reduced to within 1.5% for both DL and UL throughput, for the reference scenario.

The analysis concentrated on the statistics of receiving cross-technology signalling. Specific details regarding the periodicity of cross-technology signalling by IMT and the protocols that Wi-Fi must adhere to (such as detection periodicity, timing for vacating the channel upon detection, etc.) were not studied. These aspects require further analysis and ad hoc standardisation efforts. The impact of Wi-Fi bursty traffic was not analysed as part of the Montecarlo simulation framework - this aspect could be relevant since mobile systems are not optimized to deal with this type of interferer profile[1].

The model extension results showed that cross technology signalling had a higher chance to be received by the Wi-Fi AP when larger IMT BS EIRP was used, with 83dBm providing 87% probability of successful reception for a Dense Urban deployment. Also, the choice of cross technology signalling transmission using broadcast beams at the IMT BS resulted in a low amount of interference in the Signal to Interference and Noise Ratio (SINR) region around the chosen threshold for Wi-Fi AP detection (4dB).

2.3 Impact Assessment: benefits and counterfactual analysis

We have conducted an economic analysis to explore how sharing the U6 GHz band between mobile and Wi-Fi could be more beneficial than assigning the band exclusively to either mobile or Wi-Fi, as is traditionally done.

The study examined interference tolerance of two systems, and considered different authorisation models for Mobile and Wi-Fi, such as base station transmit power for Mobile service and Wi-Fi behaviour (i.e. Wi-Fi vacates) when concurrent use of spectrum leads to service degradation for both technologies. The results from the study indicate that both the Mobile service and Wi-Fi receivers have relatively poor interference tolerance when two deployments are within the range of cross-technology signalling messages transmitted by Mobile service base station and UE are detected by Wi-Fi AP and STA.

[1] Further insights into the impact of bursty traffic on IMT performance can be derived from the measurements conducted in WP1.

If those scenarios are eliminated, that is, orthogonalization of resources (Wi-Fi selects another channel) is triggered by reception of the cross-technology signalling messages, the study of the remaining scenarios demonstrate that from a practical perspective, the impact on both services is relatively modest. The IEEE 802.11bc based cross-technology framework could allow regulators to get insights about spectrum use that may help with authorisation regimes in the future.

The study found that the benefits of sharing are proportionately greater for mobile than Wi-Fi, particularly with higher mobile transmit powers. Note that we only considered consumer use cases for Wi-Fi and mobile and did not consider enterprise and Business to Business (B2B) use cases The relative benefits depend on the underlying assumptions related to benefits estimation[2], some of which are forward looking and still uncertain.

2.4 Risks and opportunities

In the following sections, we aim to analyse the most challenging aspects based on past experience with similar standards and regulatory topics, for both IMT and Wi-Fi.

2.4.1 Practical challenges for mobile ecosystems

Practical implementation aspects may have an impact on Mobile service performance, the extent of which would depend on the regularity and duration of the specific 802.11bc transmissions by mobile BSs and UEs. There may also be a degradation in mobile downlink and uplink capacity and coverage due to interference from WAS/RLAN equipment that fails to detect the transmitted 802.11bc signals in practice.
The impact of false alarms and missed detections were not analysed. They would depend on many factors, including detection and decoding thresholds that would be standardised[3]. To maintain mobile performance within targets, specific timing, frequency location of cross technology signalling, and detection requirements (e.g., periodicity of cross technology signalling, and WAS/RLAN behaviour in case of detection, detection thresholds, etc.) would need to be specified during the standardisation phase (e.g., in ETSI harmonised standards).

In the framework we analyse, Mobile service BSs and UEs would transmit specific 802.11bc signals in the upper 6 GHz band. From a purely hardware bill of materials perspective, this would likely not place a substantial burden on Mobile BSs or UEs, such as smartphones, given that future smartphones are expected to be capable of Wi-Fi communication in the 6 GHz band. However, there may be added complexities in the design of BSs and UEs to transmit 802.11bc signals embedded within IMT signals. In terms of software impact, the transmission of 802.11bc signals embedded within mobile signals with specific regularity and duration would necessitate changes to the software and firmware in Mobile BSs and UEs. The transmission of 802.11bc signals by mobile BSs and UEs would also result in additional power consumption, proportional to the regularity and duration of these transmissions, as they would be present in addition to the usual IMT transmissions.

[2] Detailed assumptions related to benefit calculation are provided in Real Wireless Sandbox Report D3.3 Cost-benefit findings and regulatory tools.

[3] We note that the standardization of the detection and decoding thresholds has historically been a challenging and controversial topic. Even for the 5 GHz and lower 6 GHz Radio LAN harmonized standards defined by ETSI BRAN, reaching an agreement on these thresholds took several years. We anticipate a similar debate will occur for the upper 6 GHz band, necessitating an agreement between IMT and Wi-Fi stakeholders.

There could also be added complexity and costs for operators. The proposed solution may necessitate additional interoperability testing of Mobile BSs and UEs compared to "legacy" behaviour. The time required for the effective standardisation of technical requirements and compliance tests could potentially lead to delays in the availability and use of the IMT band. Specifically, the time to market for the technical solution must account for the timelines required for the development of technology specifications at 3GPP for the proper operation of Mobile BSs and UEs, as well as the development of European harmonised standards at ETSI for the technical requirements and compliance testing.

Regarding IMT standardisation, the specifications for transmitting specific 802.11bc signals by Mobile BSs and UEs would need to be defined at least in the ETSI Task Force for European Standards (TFES), which serves as a harmonised standard across Europe. The nature of the 802.11bc transmissions, including their payload, and parameters such as regularity and duration, would need to be defined at ETSI and incorporated into the relevant European harmonised standards to capture technical requirements and compliance testing. The transmission of 802.11bc signals by IMT BSs and UEs might also require standardisation in 3GPP. This is because the functionality would be required not only in all IMT BSs and UEs (including smartphones) intended to operate in the upper 6 GHz band in Europe, but also in global devices intended to use the band in Europe (i.e. roaming scenario).

From a regulatory perspective, harmonised regulations across Europe would be ideal. A fragmented approach could lead to reduced ecosystem support and fail to maximise necessary economies of scale.

2.4.2 Practical challenges for Wi-Fi ecosystems

The implementation of protocols for Wi-Fi equipment to detect and decode the specific 802.11bc signals transmitted by mobile BSs and UEs in the upper 6 GHz band, and to subsequently take appropriate action, would require changes to the software and/or firmware in the Wi-Fi equipment. However, these changes are not expected to be substantial. The regular detection of 802.11bc signals transmitted by mobile BSs and UEs could result in additional power consumption and reduced battery life. However, this aspect can only be quantified once specific details about the required detection periodicity are standardized.

The impact on end users may arise from the limited availability of additional spectrum in certain locations and at specific times. For instance, in an urban area that is not yet covered by mobile services, there might initially be a phase where Wi-Fi access points can operate in the 6425-7125 MHz band. However, as mobile coverage expands in that area, Wi-Fi equipment will eventually need to vacate this band to accommodate mobile operations (if the mitigation technique used is W-Fi vacate). This transition could affect the performance experienced by users over time.

The evaluated XTS framework requires the development of an ETSI harmonised standard that details the detection process of the cross technology signalling and the corresponding mitigations. Associated conformance tests also need to be developed by ETSI. Given the complex nature of the problem, involving the interaction of two different technologies, only equipment compliant with the ETSI harmonised standard should enter the market. ETSI standard requirements should be mandatory. Wi-Fi equipment would have to fulfil applicable regulations and harmonised standards when entering the market. Additionally, there must be a requirement ensuring that users cannot disable or tamper with this functionality and bypass the coexistence functionality. Finally, there must be a mechanism to ensure that equipment placed on the global market without the sharing functionality cannot be used in Europe, which might imply potential standardisation impacts beyond ETSI, such as IEEE-level standardisation.

In summary, once functionality is standardised and harmonised for compliance testing as a prerequisite for market placement, it is possible to deploy Wi-Fi access points and stations in Europe. All the aspects described above would require an appropriate enforcement framework.

2.5 Implications of our evidence for future policy development and implementation strategies

The question we have examined in our economic analysis is whether sharing the U6 GHz band between mobile and Wi-Fi, facilitated by cross technology signalling, will lead to a larger benefit than assigning the band to either mobile or Wi-Fi only.

The study found that the benefits of sharing between mobile and Wi-Fi were greater than not sharing for standard IMT power and higher power deployments. The benefits are proportionately greater for IMT than Wi-Fi, particularly with higher IMT transmit powers. Note that we only considered consumer use cases for Wi-Fi and mobile and did not consider enterprise and business to business (B2B) use cases. Further, the economic analysis has been carried out assuming fair treatment of mobile and Wi-Fi, i.e. that the band is made available for use at the same time. This gives a comparison independent of regulatory decisions. The relative benefits depend on the underlying assumptions, some of which are forward looking and still uncertain. In particular, the following factors should be considered when considering policy development in the U6 GHz:

- Possible emergence of new applications could change the WTP for both mobile and fixed broadband. If such applications are unique to one service e.g. require mobility or very high data rates, it could again affect how benefits are split between IMT and Wi-Fi.
- The potential importance for deploying U6 GHz in allowing MNOs and Wi-Fi service providers to deploy larger channels in mid-band spectrum; Larger channels compared to those available in current harmonised bands would be particularly beneficial for targeted innovative new services that require larger bandwidth.
- Foundational technologies and associated new applications of 6G and Wi-Fi7 have the potential to radically change the benefits for IMT and Wi-Fi.
- Rollout, and more importantly, adoption of 6GHz capable equipment could happen at different speeds for IMT and Wi-Fi.

The feasibility of enabling spectrum sharing between mobile and Wi-Fi networks needs to be thoroughly examined, taking into account the practical challenges faced by both ecosystems. Developing a successful and effective sharing framework will require significant design and implementation time and dependence on a standardisation process. Creating standards will take time, and developing technical minimum requirements and associated conformance testing will be essential. This process must engage various technology stakeholders to build confidence in the efficacy of the sharing solution. Additionally, an enforcement framework is necessary to take necessary actions in the case of failure to implement the interference mitigation techniques. There should also be mechanisms to ensure that devices sold after the standards are established cannot alter their behaviour through software or firmware modifications. Furthermore, there is a need to explore the challenges of making XTS a reality in consultation with relevant stakeholders to allow IMT and Wi-Fi to operate effectively in a shared scenario. This effectively minimises any potential technology barriers and risks to any deployments. Moreover, harmonisation would allow development costs to be shared and minimise the impact on equipment costs.

Our study explored the most commonly discussed options within CEPT PT1. While reduced IMT power was not a popular option, it was still analysed as a boundary case to illustrate its potential outcomes. Other Wi-

Fi and mobile sharing options may arise as a result of the ongoing CEPT study on this topic. At the time of this report, we considered the most commonly discussed options for sharing. As new options emerge, conducting the technical analysis and conducting CBA to assess the relative net benefits of the sharing solutions would be helpful.

3. Technology pair 2 - Independently operated private networks in the upper n77 band

Independently operated private networks in the upper n77 band[4]: The SAL framework in the UK provides a mechanism to access frequencies locally. In their consultation [**4**] published in November 2023, Ofcom reported on the increasing demand for shared spectrum within the UK and in several other countries adopting similar approaches.

There is significant interest in the industry in the use of private networks in the n77 band. This shared access spectrum is the most important source of private network spectrum, especially for 5G technologies where there is a wide variety of devices available. Private networks are critically dependent on the availability of spectrum; therefore, maximising spectrum availability is of crucial importance to enabling innovation and commercial usage, especially where demand is likely to be high, such as in urban areas.

In the consultation Ofcom explored the potential adjustments to enhance spectrum supply to meet further growth. The focus of our study was test urban deployments as this is where there is highest demand for spectrum, therefore the benefits of any policy or coordination methodology changes are likely to be greatest here.

3.1 Objective of the Private networks sandbox study operating in the n77 band

We assess 2 study questions:

1. Study question 1- Better Data: "The extent to which deployed network equipment and user devices can make measurements of the radio environment that can inform regulatory operational and policy activities and form the basis of more adaptive and dynamic spectrum authorisations in the future." Private networks are critically dependent on the availability of spectrum. Spectrum accessed through the SAL framework is the most crucial spectrum source available to private networks in the UK. Maximising spectrum availability is vital to private network services, especially in high-demand areas such as urban areas. Ofcom relies heavily on signal strength prediction models in its coordination process, therefore the accuracy of these models is vital. In particular they predict the size of the "sterilisation area" around a proposed deployment. The objective of the sandbox was to assess the accuracy of the propagation prediction model used by Ofcom, and a ray-trace prediction model (the "project model") of the type commonly used by MNOs, by comparing with measurements. The measurement data was collected via high quality continuous wave (CW) surveys around several sites in central London in the upper n77 band. The analysis will help inform spectrum policy and coordination decisions, and should result in greater spectrum availability with reduced interference risk.
2. Study question 2- "Interference tolerance: How much more intensively can different services and deployments share spectrum without causing harmful interference to each other?" As the next step, we tested the following hypothesis: incremental interference due to intense spectrum sharing could be acceptable when the interference does not result in an unacceptable service level

[4] Upper n77 band refers to 3.8 - 4.2 GHz

degradation. The test plan aims to benchmark and evaluate the impact of co-channel interference from a neighbour cell on user experience. Our goal is to understand how the addition of interference from neighbouring cell(s) impacts the end-user service experience for applications such as voice and video. We do that by leveraging the collated experimental data to profile the impact of interference on the end user service requirements, e.g. the correlation between increased UE Physical Data Shared Channel (PDSCH[5]) SINR on the received application DL throughput and subsequent impact of the end user service requirements for applications such as voice and video. The analysis of the experimentation data using data analytics techniques will provide insights for us to test our hypothesis that the end user service/experience degradation due to spectrum sharing could be acceptable to some user applications and services. The solution envisaged from this experimentation is one where multiple private networks operating in the same frequency band can minimise the geographical separation from each other

3.2 Insights from Interference prediction model improvement for SAL framework

3.2.1 The status quo and problem statement

The focus of this part of the study was interference predictions, which are used by Ofcom to define n77 shared spectrum policies such as EIRP limits in urban areas, and to coordinate licences. Ofcom's predictions are based on an International Telecommunication Union-Radiocommunication (ITU-R) recommendation which assumes a single radio path over any clutter such as buildings. Additionally, clutter height is generalised to average values at 50 m resolution. MNOs on the other hand tend to use ray-trace models which allow multiple radio paths around, over and through buildings, together with building height data at around 1 m resolution in urban areas.

In their November 2023 consultation, Ofcom published predictions of the number of premises and area "sterilised" in various scenarios. These predictions were hugely pessimistic compared to those typically generated by ray-trace tools. Ofcom subsequently issued a correction [**5**] to their sterilised premises predictions. Nevertheless we note there are currently only 5 SALs in the City of London (CoL) despite the high spectrum demand there.

3.2.2 Proposed solution

Our hypothesis was that ray-trace tools would provide more accurate predictions, allowing greater utilisation of the n77 SAL band compared to Ofcom's predictions. This was tested by:

- Collecting CW survey data from 6 Freshwave-managed sites in the CoL; we believe this data, delivered to DSIT, is unique as the n77 band has only become available relatively recently and there are few existing sites in CoL with antennas suitable for CW transmissions
- Using this data to calibrate the project ray-trace model; this is standard practice when this type of model is used in a new area with little or no existing data
- Obtaining predictions of Received Signal Strength Indicator (RSSI) from Ofcom from 3 of the 6 sites, using an updated model based on ITU-R Recommendation P.452-18
- Comparing predictions from the project model (sterilised areas and numbers of premises etc.) with Ofcom predictions and the survey data

[5] PDSCH is a downlink physical channel that deliver user data from 5base station to UE

3.2.3 Impact Assessment: benefits and counterfactual analysis

The benefits of more accurate predictions are better policy decisions, for example on power limits, and greater certainty in evaluating the interference risks of SAL applications. Figure 3 is a comparison of the Ofcom and project model predictions for one of the six sites. These are very different in appearance: the project model predictions show much more detail around streets and buildings, and RSSI decreases much more rapidly with distance from the site.

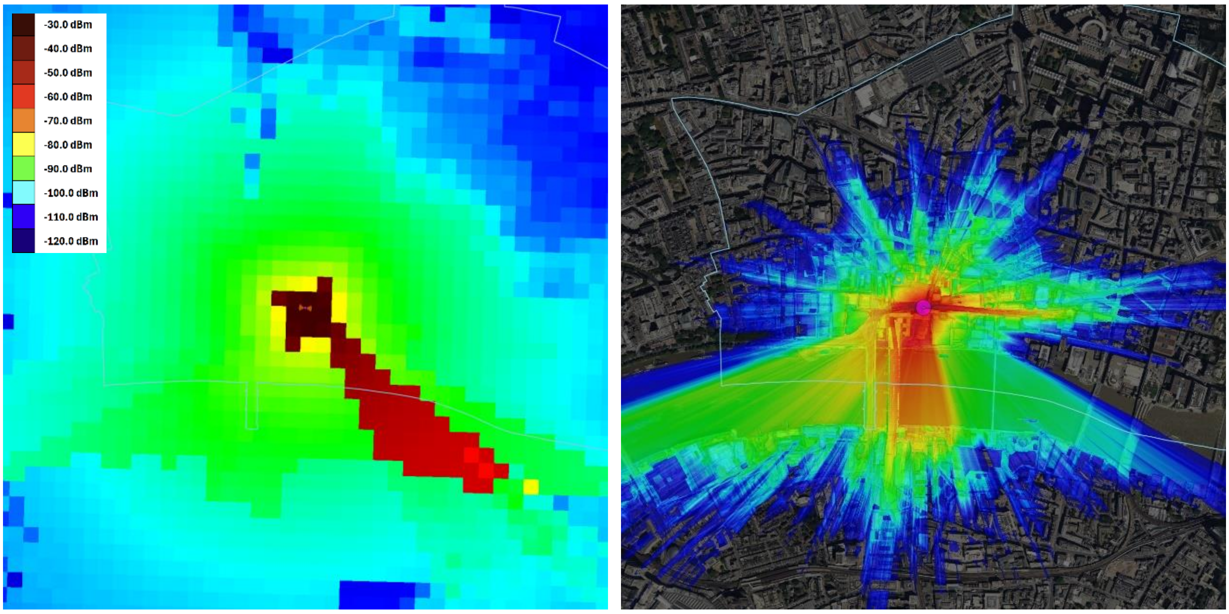

Figure 3: Ofcom (left) and project model (right) predictions of RSSI for a 2 x 2 km area for an omni antenna at the same site. The colour legend (top left) applies to both predictions.

Further analysis, when the survey antenna patterns were included in the predictions, showed the project model predictions were closely aligned with the survey data giving a typical deviation from measurements of 6-8 dB, compared to 15-24 dB for Ofcom's predictions, as shown in Table 1 below.

Table 1: Root Mean Square (RMS) differences between surveyed RSSI and the Ofcom and project model predictions for each of the 6 surveys at the 3 sites for which we have Ofcom predictions.

Survey ID	Ofcom RMS (dB)	Ov1 RMS (dB)
Loc2B5	15.3	7.6
Loc2B7	19.0	6.1
Loc9A5	21.6	6.3
Loc9A7	24.3	6.7
Loc10A5	15.4	7.5
Loc10A7	17.3	6.7

Further details on the methodology and analysis are given in deliverable D1.5.

Overall the results show:

- Ofcom’s input data and prediction resolution (50 m) is much coarser than the project model (1 m), leading to much less street- and building-level variability in the predictions
- Ofcom’s predicted sterilised area and list of sterilised premises shows significant differences to the project model
- Ofcom’s predictions appear to show small regions close to each site with anomalously high RSSI values
- Ofcom’s predicted RSSI decreases with range at a rate which is close to free space, whereas project predictions and surveys show much faster rates
- The project model gives much more reliable estimates of RSSI and would therefore result in better coordination decisions than Ofcom’s model

3.2.4 Risks and opportunities

Better modelling of interference presents opportunities for greater utilisation of this valuable spectrum resource, for innovation and commercial and other uses, e.g. for multisite local government private networks and neutral host networks.

Potential risks however are:

- More SALs will inevitably increase the interference risk to existing SAL licensees, although the risk should be manageable through coordination using the appropriate modelling tools.
- Deterministic models, such as ray tracing models, may need calibration with measurement data and are more complex to implement nationwide. On the other hand MNOs etc. and their tool providers have decades of experience of managing interference risk in both rural and urban areas.

3.2.5 Implications of our evidence for future policy development and regulation

More accurate predictions would present a number of opportunities related to policies and coordination. Firstly around policies, some of the proposals in Ofcom’s November 2023 consultation were based on overly pessimistic predictions of sterilised area. This resulted, for example, in EIRP constraints which are too restrictive to enable contiguous outdoor private networks in cities, and other constraints which prevent usage for public mobile services.

Secondly around coordination, inaccurate predictions could result both in licences being granted where they will interfere with existing services, and licence applications being rejected where the risk of interference to existing services is minimal. More accurate predictions would inevitably require a reduced margin, and therefore greater intensity of sharing, whilst maintaining protection of existing services. Mobile operators invest in more accurate ray-trace modelling so they can minimise deployment costs and maximise spectrum utilisation.

Furthermore, given the complexity of the problem and the investment needed to develop such solutions, it is fundamental that both the regulatory framework and required standards are in place before any device enters the market. The standards need to cover both technical minimum requirements and associated conformance testing. The standardisation process would also help technology stakeholders to build confidence in the effectiveness of the sharing solution.

The enforcement framework should also provide enough confidence for MNOs to invest in the band. Whatever the standardised sharing approach will be, there should be a mechanism in place to ensure that devices sold after market cannot alter their behaviour through software and/or firmware modifications.

3.3 Interference tolerance measurements and licensing process improvement

3.3.1 The status quo and problem statement

This section presents the key insights from the Spectrum Sandbox Project, focusing on the feasibility and effectiveness of independently operated private networks in the upper n77 band. The findings are drawn from various test campaigns, covering interference tolerance, data-sharing mechanisms, and regulatory considerations. The objective is to assess spectrum-sharing capabilities, align conclusions with study objectives, and propose next steps for enhanced spectrum utilisation.

The increasing demand for private 5G networks, particularly in dense urban environments, presents challenges for efficient spectrum utilisation. Traditional spectrum management models do not fully support dynamic interference management, limiting opportunities for more intensive spectrum sharing among independent private networks. Ensuring that multiple independently operated private networks can coexist in the upper n77 band (3.8 – 4.2 GHz) without causing harmful interference requires a data-driven approach to spectrum coordination.

Digital Catapult's experiments addressed one of the three focus areas highlighted in Ofcom's Spectrum Management Strategy [**6**], namely promoting spectrum sharing through improved data and more sophisticated analysis when assessing the conditions for sharing. In this context, we evaluated the feasibility of spectrum sharing for independent private 5G mobile networks operating in the upper n77 band (3.8 – 4.2 GHz). Our hypothesis postulated that incremental interference due to intense spectrum sharing could be acceptable when it does not result in an unacceptable level of service degradation. Additionally, the study explored the role of emerging technologies, such as Data Analytics, in profiling spectrum usage and assessing the conditions for spectrum sharing, thereby facilitating more efficient utilisation of the finite spectrum resource.

The findings provide valuable data to inform regulators on spectrum sharing, offering insights into the conditions under which networks can coexist with minimal service degradation. The study also proposed a service-aware licensing approach, where licensing conditions consider the type of 5G applications deployed. By aligning licensing decisions with application-specific interference tolerance levels, regulators can create a more flexible and responsive spectrum management framework.

3.3.2 Proposed solution

As private 5G networks continue to expand, efficient spectrum management has become increasingly critical. This project focused on how multiple independent private networks can coexist in shared spectrum environments, maintaining optimal performance while minimising interference. By utilising real-world measurement data and advanced analytical frameworks, the study provides actionable recommendations for dynamic spectrum coordination, improvements in regulatory policy, and technical innovations aimed at enabling more intensive spectrum sharing.

In particular, the study tackles the challenges of spectrum sharing in the upper n77 band by proposing a data-driven approach designed to enhance spectrum utilisation. The solution combines structured interference management with service-aware licensing. Together, these strategies allow private 5G networks to coexist more effectively in shared spectrum environments, enhancing performance and optimising spectrum usage.

A key component of the solution is the Interference Impact Metric (IIM), which quantifies the effects of interference by correlating SINR, application throughput, and PRB utilisation across different deployment scenarios. This approach has enabled the study to evaluate spectrum sharing between similar and different service types, demonstrating that interference can be managed dynamically without severely impacting network performance.

Some of the key aspects for the activities covered are:

- The project demonstrated that independently operated private networks in the n77 band could effectively share spectrum with appropriate interference management.
- The interference tolerance tests demonstrated that co-channel interference affects network performance. However, 5G technology incorporates inherent mechanisms e.g., Channel State Information - Interference Measurement, Inter-Cell Interference Coordination etc. to mitigate interference.

  Furthermore, 5G applications have distinct service level requirements, as specified in 3GPP and The European Telecommunications Standards Institute (ETSI) standards. This means that each use case, whether enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), or massive machine-type communications (mMTC)—operates optimally under varying network conditions.
- Metrics such as SINR, Physical Resource Block (PRB) utilisation, and Block Error Rate (BLER) showed degradation under high-interference conditions, reinforcing the need for adaptive interference mitigation strategies.
- The introduction of the IIM provided a structured approach to quantifying interference effects and supporting real-time decision-making for network optimization.
- The Measurement Translation Engine processed raw network measurements into structured datasets, enabling more effective regulatory oversight and interference assessment.

Interference Impact Metric (IIM)

The introduction of the measurement translation engine has facilitated data processing, allowing for a more precise assessment of interference conditions and spectrum usage trends.

The framework for the generalised IIM was derived by combining fundamental 5G performance indicators that directly reflect the impact of interference on network efficiency and user performance. It synthesises field measurement practices in a weighted linear combination of normalised metrics. The key components were determined by:

- SINR impact: SINR is a primary determinant of network quality. The term $\mathbf{1}-\left(\frac{\boldsymbol{SINRMeasured}}{\boldsymbol{SINRIdeal}}\right)$ models the degradation in signal quality due to interference. It is derived from the Shannon-Hartley theorem [7] and 3GPP recommendations for interference modelling.
- Throughput efficiency: The ratio $\frac{\boldsymbol{TApp}}{\boldsymbol{TL1}}$ compares the application-layer throughput with the physical-layer throughput to capture transport inefficiencies caused by interference (e.g. retransmissions or scheduling delays).

- PRB utilisation: The efficiency of physical resource block usage, modelled as $\mathbf{1}-\frac{\boldsymbol{PRBUsed}}{\boldsymbol{PRBTotal}}$, reflects congestion and interference-induced resource contention. It incorporates principles of spectrum utilisation modelling as seen in private 5G networks.
- Weighting factors: Weights (w1, w2, w3) are included to calibrate the relative importance of SINR, throughput, and resource utilisation. These weights can be adjusted based on specific deployment scenarios, such as urban environments where interference and spectral efficiency are critical and cater to different use cases centric to private 5G networks.

The proposed generalised formula for calculating the IIM is:

$$\boldsymbol{IIM = w1\,.\left(1-\frac{SINRmeasured}{SINRIdeal}\right)+w2\,.\left(1-\frac{TPApp}{TPL1}\right)+w3\,.\left(1-\frac{PRBUsed}{PRBTotal}\right)}$$

Where:

- **w1, w2, w3**: Weights reflecting the relative importance of SINR, throughput, and PRB utilisation.
- **PRBUsed/PRBTotal**: Captures spectrum utilisation efficiency. A higher ratio may indicate congestion or inefficient sharing.
- **SINRIdeal**: This reflects the ideal SINR value in Excellent radio condition.

Test Results and Findings

The field trials conducted with two private networks in central London replicated real-life propagation challenges while effectively isolating unwanted wireless impairments.

- The measurement results and IIM findings indicated:
  - For Transmission Control Protocol (TCP) downlink scenarios, IIM increased significantly in Good and Fair regions, indicating strong interference impact. The Poor region saw a marginal decrease due to interference saturation effects.
  - For TCP uplink scenarios, Increased IIM across all regions, with the highest degradation in the Poor region due to TCP's congestion control mechanism misinterpreting interference as congestion.
  - For User Datagram Protocol (UDP) downlink scenarios, Fair region experienced the highest increase in IIM, while the Poor region showed a slight decrease due to interference saturation.
  - For UDP uplink scenarios, Increased IIM across all regions, with the most pronounced impact in Fair conditions due to UDP's lack of congestion control.
- The Measurement Translation Engine converted raw interference data into actionable insights, enabling accurate IIM calculations for different deployment scenarios
- The results revealed that while spectrum sharing introduces performance degradation, the impact can be mitigated through intelligent interference management strategies

3.3.3 Impact Assessment: benefits and counterfactual analysis

If our top down assessment is borne out in terms of actual demand for Private Mobile Network (PMN) licences, the current Ofcom methodology will be a brake on PMN deployment in urban and suburban areas and may restrict the potential for the PMN market to grow faster than predicted by industry analysts.

The analysis gives a strong indication that allowing more accurate measurements has a significant impact on the benefits. The costs appear quite low in comparison to the benefits, but it would be useful to get a more in-depth view of the potential resources and associated costs of an automated database system, supported either by spectrum observatories or sensors.

Clearly, the acceptable level of coverage degradation allowed in setting the separation distances can have a major impact on the net benefits and DSIT/Ofcom will probably have to consult and make a judgement on this.

It would be useful to carry out more research on the real-world impact on the PMN user experience and value of allowing limited levels of coverage degradation as modelled in the simulations.

The issue examined in this analysis is whether moving from sharing the n77 band with separation distances based on Ofcom's I/N target to separation distances based on more accurate interference measurements, underpinned by an automated system for accessing the spectrum, could increase the overall welfare benefit.

Our analysis strongly suggests that an automated system based on more accurate interference measurements will lead to a significant increase in the benefits from private mobile network use and this policy direction should be pursued.

Though subject to some caveats over the assumptions made, our analysis also suggests that the current Ofcom approach will be a brake on PMN deployment in urban and suburban areas as currently forecast, as well as restricting the potential for the PMN market to grow beyond this level.

Costs appear quite low in comparison to benefits, but it would be useful to get a more in-depth view of the potential resources and associated costs of an automated database system, supported either by spectrum observatories or sensors.

3.3.4 Risks and opportunities

Introducing a requirement for private network users to specify 5G application usage and minimum performance metrics in the license application process presents both benefits and challenges. While this approach enhances transparency and ensures efficient spectrum utilisation, it may also introduce practical difficulties for applicants who lack the technical expertise to provide such details. This section explores the practical difficulties of this requirement and potential solutions to make the process more feasible.

Challenges to the licensing framework

- Limited technical knowledge among users: Many private network users, especially enterprises without deep telecom expertise, may not fully understand how to define the throughput and latency needs for their intended 5G applications.
- Dependence on network operators and vendors: Many private networks rely on network providers or vendors for deployment, and they may not have direct access to performance metrics or understand how these metrics translate into practical needs of the 5G applications.

- Difficulty in translating business needs into network requirements: Businesses often think in terms of operational outcomes rather than network specifications. For example, a manufacturing plant may require real-time control of robotic arms but may not know how that translates into a 5G specific performance requirements.

Potential solutions to improve practicality

- Simplified user guidance: Clear documentation, Frequently Asked Questions (FAQs), and interactive tools could assist users in estimating their network requirements without the need for deep telecom expertise.
- Collaboration with vendors and consultants: Users could be encouraged to work with equipment vendors, telecom operators, or industry consultants who can help assess and provide the necessary data pertaining to the 5G applications requirements.
- Iterative process and flexibility: The system could allow users to submit an initial estimate, followed by a refinement stage where Ofcom provides feedback or recommendations.

3.3.5 Implications of our evidence for future policy development and implementation strategies

Based on the experiments conducted during the project an amendment to the existing licensing process is also recommended to accommodate intensive spectrum sharing in the SAL spectrum; thus, effectively utilising the network resources without impacting the user experience in overlapping private networks. The flowchart presented in Figure 4 depicts the proposed process for evaluating and approving new licence applications for a private network user. The process involves several steps, including:

1. **Licence application**: The process begins with a private network user agreeing to the licence application terms of sharing additional information in the application form including the list of 5G applications to be deployed in the network and the minimum performance requirements of operation for the mentioned 5G applications.
2. **Ofcom query database**: Ofcom queries its database to check for existing deployments in the area and assess potential interference and potential scope for additional deployments. The database contains information on SINR and tolerance levels for different applications.
3. **Licence application evaluation**: The new licence application is evaluated against the interference threshold.
4. **Licence application outcome**: If the application meets the criteria, it is approved. Otherwise, it is rejected.
5. **Conduct measurement campaign**: If the licensee is successful in the application, then the licensee will conduct campaigns to gather data on the network's performance and share the results with Ofcom to update the database.

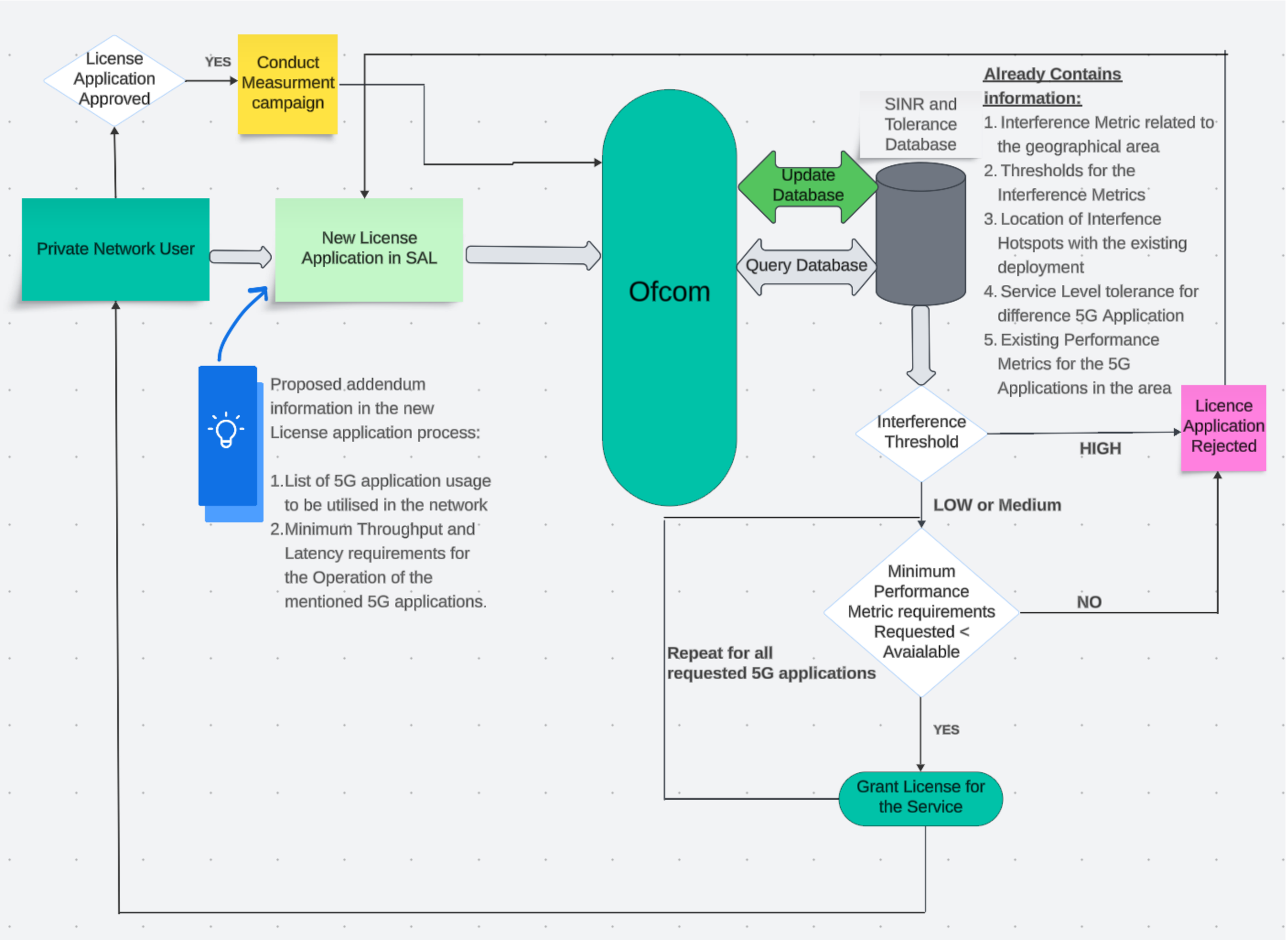

Figure 4: Shared access licence application process

The proposed licensing process for the SAL spectrum is designed to follow a standardised approach for all 5G applications, evaluating interference thresholds and performance metrics uniformly, ensuring fair and efficient spectrum usage. This neutrality is achieved through a standardised evaluation framework that assesses the network's ability to accommodate additional deployments based on interference metrics rather than the nature of the application itself.

The integration of IIM into SAL frameworks provides an adaptive approach to regulatory decision-making, allowing spectrum allocation to be more dynamically adjusted based on real-world interference conditions. By aligning licensing decisions with network performance data, regulators can enhance spectrum utilisation and minimise sterilised areas. The end-to-end process for data collection, processing, management, and sharing is illustrated in Figure 5.

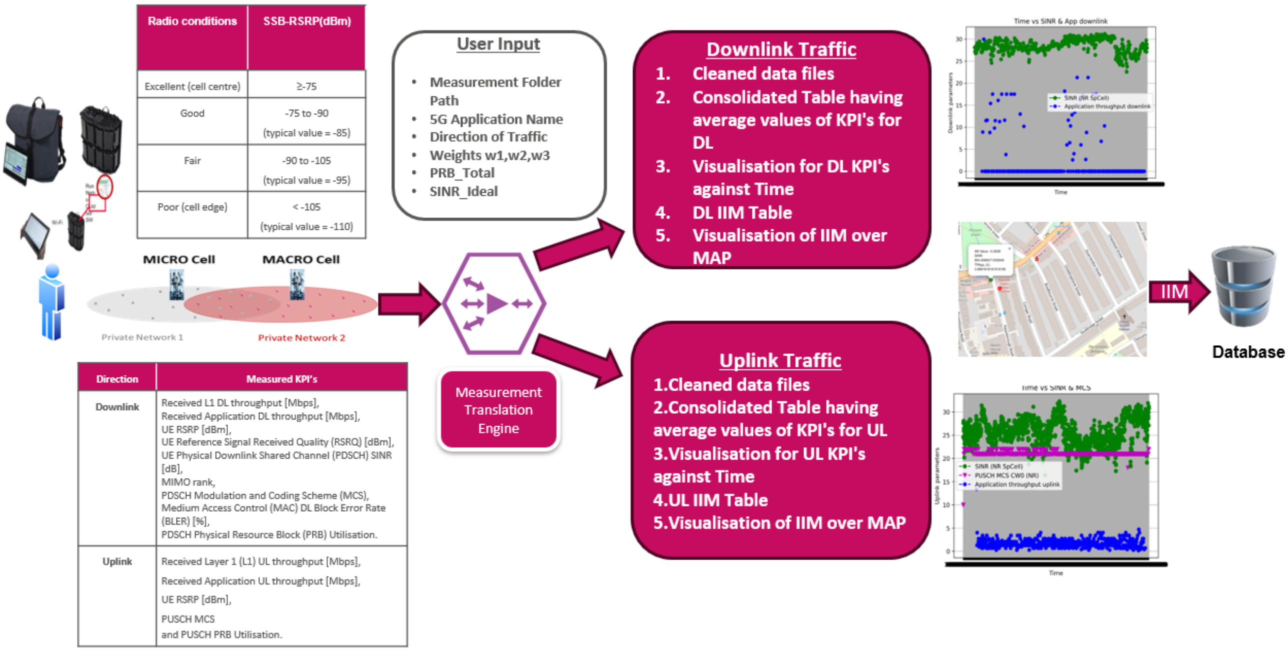

Figure 5: E2E process for IIM translation from raw measurements

Next steps for building on objectives and study questions and lessons learnt

- Further analysis of large-scale 5G private network deployments to refine interference mitigation strategies.
- Implementation of automated spectrum coordination mechanisms based on IIM insights.
- Optimization of power control and adaptive bandwidth allocation for better spectrum efficiency.
- Deployment of the Measurement Translation Engine in real-world regulatory environments to improve data-driven spectrum management
- PoC demonstrations to test adaptive interference mitigation in private networks.
- Development of real-time visualisation tools for interference impact analysis to support regulatory decision-making.
- The current approach used specialised test and measurement equipment, Nemo outdoor backpack for conducting the measurement campaign. It is worth noting the following known challenges for extracting meaningful user specific data from the base station which needs to be addressed to move the measurements collection to base station.

  - The UE report measurements to the base stations. However, these are aggregated values and indicate a range of interference levels and do not provide granularity which can be measured on the UE. For example, during the Channel State Information (CSI) reports from UE to the base station the Channel Quality Indicator (CQI) will be reported, and it is based on a channel model where a particular value of CQI corresponds to a range of SNR values.

  - Most base station vendors do not expose the low-level UE measurement reports indicating the channel quality per subframe.

  - The amount of low-level data gathered will be very high when captured from the base station since the UEs report on a transmission time interval of 1 msec. This could impact base station performance and stability if the logging is enabled for all the UEs connected to the base station.

- It is very challenging to segregate the user and control traffic for different mobile devices at the base station and the algorithm will need to implement complex state machines.
- Data gathered from the base station will not be able to identify the physical location of the UE and would need implementation and deployment of specialised feature on the base station.

4. Future directions and the role of AI in spectrum management

This section explores how key concepts from the sandbox project, along with emerging ideas, can help adapt spectrum management. Specifically, it examines the role of automation and AI in enhancing spectrum management.

The UK has a unique opportunity to lead in AI-driven spectrum management. The Government's AI Opportunities Action Plan emphasises the importance of leveraging AI for economic growth and improving public services. At the same time, Ofcom's Spectrum Roadmap highlights the need to embrace new technologies and innovations, as well as to leverage data for better spectrum management.

These initiatives align with the overarching goal of DSIT, which is to accelerate innovation, investment, and productivity through world-class science. This effort aims to ensure that new and existing technologies are developed and deployed safely across the UK, ultimately benefiting its citizens.

Understanding the rapid developments in AI technology and applying them across various sectors aligns with broader government policy. In the Spectrum Statement, the Government emphasised that spectrum management should encourage innovation and investment while focusing on consumer outcomes. To maximise the benefits of innovation in spectrum applications and services, it is essential to consider the need for targeted support for spectrum-focused innovations, including the opportunities presented by spectrum sandboxes.

The pace of innovation in technology necessitates continuous updates to regulation to ensure it remains effective. The potential for using AI to enhance spectrum management is substantial, mainly through dynamic decision-making and real-time adaptability. Data-driven tools and algorithms facilitate informed decision-making in spectrum management. Established and emerging AI techniques could fundamentally transform existing procedures related to spectrum management.

It is crucial to address the practical aspects of implementation and adoption. This includes evaluating the regulatory, operational, and data requirements and providing recommendations for inputs to be considered in a future cost-benefit analysis. Such analysis would assist regulators and organisations in assessing the feasibility of integrating potential AI techniques into spectrum management. We propose further exploration in the following areas.

1. Make use of the path loss measurements improve the license conditions

If the transmitted power and the receive power levels can be extracted from radio transmitters and receivers, the pathlosses between the transmitter and the receiver can be extracted and gathered in a database at various frequencies and various locations. The data will vary depending on the changes in the environment i.e. new buildup etc. The use of AI/ML algorithms will help in processing this data to tune the propagation models Ofcom use for various licensing purposes and make more accurate predictions to improve the accuracy. As an example case study, mobile operators use this principle to build a comprehensive and more accurate coverage prediction tool to predict the coverage of their mobile network. The improvements made based on the drive test data make it a unique and accurate model.

Better data will enable understanding real world conditions resulting in developing more accurate technical conditions for licenses. Less restrictive technical conditions will enable immediate benefits by encouraging investment and accepting adoption

2. Licence assignments

With the understanding of path loss measurements and technology-specific parameters, AI could enable more dynamic, data-driven coverage and interference predictions, which can be further extended to self-service licensing through intelligent automation. Our n77 sandbox experiment investigated the interference tolerance ability for 5G private networks to minimise the separation distances between private networks. This work can be further extended using AI, to allow users to make intelligent trade-offs based on their interference tolerance and protection needs. This could lead to more efficient spectrum use while maintaining appropriate protection for existing users. The beta version of Ofcom's online mapping tool is designed to provide an indicative overview of spectrum availability at specific locations. Any existing information, such as the mapping tool and existing license information, could be valuable inputs for new licence applicants to understand the likelihood of succeeding in their licence application.

3. Visibility on connectivity

Ofcom's vision for wireless connectivity and its commitment to spectrum efficiency rely on high-quality data—one of the themes for future work—to inform metrics for decision-making, specifically Key Performance Indicators (KPIs). The effectiveness of coverage obligations and the selection of appropriate KPIs significantly influence our ability to achieve universal connectivity.

Data collected from various sources, such as crowdsourcing, UE reporting, and consumer complaints, can be used to create a connectivity metric. AI can help translate this data from different sources into a format that consumers and regulators can easily understand, ensuring compliance with coverage and minimum requirements.

Key areas to explore include identifying what data is available for collection, determining the sources from which this data can be obtained, and figuring out how to present this data using AI. This will help inform connectivity status and improve policy decisions.

AI could also facilitate spectrum monitoring by implementing signal strength measurements to ensure that coverage obligations are met and transmissions are below specified thresholds in exclusion areas. AI algorithms could analyse real-time data to flag potential compliance issues before they adversely affect services.

4. Visibility on Interference and improved sharing frameworks

Ofcom's objective of efficient use of spectrum can sometimes present contradictions. Efficient use of spectrum can be subjective depending on the service, user requirements, and licence conditions.

Coordinating and managing spectrum use between different services belonging to various users incurs some administrative burdens. Automation, where possible, could minimise delays arising from these administrative activities.

Additionally, the lack of real data and the desire to accommodate future deployments lead traditional regulators, such as Ofcom, to adopt a conservative approach. This often results in excessively restrictive license conditions designed to protect services, ultimately causing inefficient spectrum usage and hindering investment. Lessons learned from international approaches could aid in developing more adaptive spectrum-sharing frameworks in the UK. Such frameworks could leverage multiple data sources that are currently siloed and not effectively utilised.

Currently, license conditions are derived from theoretical I/N calculations based on generic assumptions related to service type, antenna type, and transmission power, among other factors. However, variables such as antenna patterns, height, transmitted power, and environmental clutter can change over time and from location to location. These generic fixed assumptions often lead to inefficiencies. Furthermore, coverage predictions rely heavily on the accuracy of the models used. Our experiments in the n77 band have shown that accurate coverage predictions lead to improved efficient use of spectrum.

AI could be pivotal in integrating various requirements and data types to estimate the conditions for a dynamic sharing framework. It can utilise local environments, clutter, terrain data, weather conditions, and historical trends to provide more accurate license conditions, resulting in more efficient sharing frameworks.

The availability of datasets is a significant step toward facilitating AI adoption. Our sandbox experiment collected real-time measurement data from near commercial live networks in challenging environments, such as central London, representing the first instance, to our knowledge, where such datasets are available.

This sets a precedent for future measurement campaigns and illustrates how data can be analysed and utilised for regulatory purposes. Further work utilising this dataset and the adoption of AI could elevate this proof of concept to the next level.

5. Recommendations for further work

This section offers recommendations for additional work.

5.1 Mobile and Wi-Fi sharing

The field rials demonstrated performance for static deployments of devices and a fully loaded network. To gain further insight into the IEEE 802.11bc based cross-technology signalling framework, the following areas should be studied further:

- Periodicity of cross technology signalling message transmissions and receiver sensitivity requirements for Wi-Fi equipment
- Mobility scenarios, and how it related to cross-technology signalling transmission periodicity and receiver sensitivity requirements
- Performance under partial loading and utilisation of energy savings features.
- MIMO performance should be investigated further. Field trials included results with rank 1[6] transmissions from the mobile system, providing mobile UE more degrees of freedom to spatially suppress Wi-Fi interference than if rank 2 or higher were utilised.

[6] Rank 1 transmission in mobile systems refers to sending a single data layer over a MIMO system, even when multiple antennas are available. This occurs in high-correlation channels where spatial multiplexing is ineffective. Instead, beamforming or transmit diversity enhances signal quality. While Rank 1 limits data rates compared to higher-rank transmissions, it improves reliability and coverage in challenging conditions.

- Practical implications if Wi-Fi STA does not monitor cross technology signalling. The field trial results demonstrate that if only Wi-Fi AP is enabled to receive cross-technology signalling, IMT performance may be degraded by Wi-Fi STA connected to Wi-Fi AP outside the cross-technology signalling range. How often such scenarios occur in practice requires further testing over a large area representative of a macro deployment, which was not in scope of this study.
- From IMT perspective, we stress that it is critical that the functionality is properly standardised, harmonised and compliance tested as a pre-condition for deployment.
- Consider Wi-Fi adoption from enterprises: That would involve getting details on underlying enterprise data connectivity spending and trends, number of business/enterprise Wi-Fi APs and individual end-users and disaggregating business and residential broadband from the total fixed broadband connections currently in the model.
- Assess the impact of delayed deployment of one technology, i.e. IMT as Ofcom proposed in the latest consultation. If the use of U6 GHz by IMT lagged behind Wi-Fi, far fewer Wi-Fi APs would need to vacate in the early years,

5.2 Independently operated private networks in the upper n77 band

Further work could include:

- Assessment of the performance, and suitability for coordination, of available ray-trace prediction tools
- Using such tools to assess the impact of specific policy changes such as allowing higher EIRPs
- Collecting further CW data in other types of urban environments for comparison with Ofcom and other predictions
- Conduct more research, along with stakeholder consultation, into acceptable levels of coverage degradation and their use in setting separation distances, as this has a major impact on the projected net benefits. This may require further research on real-world impacts on user experience and private mobile network value under different specifications of coverage degradation.
- Extending Large-Scale Deployment Trials:
    - Conduct further trials in diverse urban, suburban, and rural environments to assess how spectrum-sharing principles apply across different network densities.
    - Expand testing with additional private network operators to evaluate the impact of multiple coexisting networks within the same spectrum band.
- Utilising Base Station Measurements Instead of UE-Based Metrics

    - Explore collecting interference and performance metrics directly from base stations rather than relying on specialised test and measurement kits for collecting data from mobile devices.
- Refining the IIM metric:
    - Expand the IIM framework to incorporate a wider range of performance indicators, such as latency, jitter etc.
    - Further research is needed to determine how different network deployments should be weighted within the IIM framework.
- Service aware Licence process: Work with regulators to develop and refine the dynamic SAL model, incorporating spectrum monitoring and service-aware licensing.

6. References

1 Ofcom Consultation, Expanding access to the 6 GHz band for mobile and Wi-Fi services Proposals for AFC in Lower 6 GHz and mobile / Wi-Fi sharing in Upper 6 GHz, 13 February 2025.

https://www.ofcom.org.uk/spectrum/innovative-use-of-spectrum/consultation-expanding-access-to-the-6-ghz-band-for-commercial-mobile-and-wi-fi-services/

2 Ofcom publication on Mobile and Wi-Fi in Upper 6 GHz Why hybrid sharing matters, Published 21 May 2024, https://www.ofcom.org.uk/__data/assets/pdf_file/0023/285710/mobile-and-wi-fi-in-upper-6-ghz.pdf

3 Ofcom consultation: Hybrid sharing: enabling both licensed mobile and Wi-Fi users to access the upper 6 GHz band, available at: https://www.ofcom.org.uk/consultations-and-statements/category-1/hybrid-sharing-to-access-the-upper-6-ghz-band

4 Supporting increased use of shared spectrum: A consultation on proposals to enhance our Shared Access framework to support a growing variety of spectrum users", Ofcom (Published November 2023).

5 Technical modelling correction to Table 5.3 of 23 November 2023 consultation, https://www.ofcom.org.uk/siteassets/resources/documents/consultations/category-1-10-weeks/consultation-supporting-increased-use-of-shared-spectrum/associated-documents/shared-access-technical-modelling-correction.pdf?v=360925

6 OFCOM "Supporting the UK's wireless future Our spectrum management strategy for the 2020s", https://www.ofcom.org.uk/__data/assets/pdf_file/0017/222173/spectrum-strategy-statement.pdf

7 https://en.wikipedia.org/wiki/Shannon%E2%80%93Hartley_theorem

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